Water use across a catchment and effects on estuarine health and productivity

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Objectives

1. To complete an investigation of environmental flow regimes required to maintain the health and production of oysters from the Little Swanport estuary through continued collection of environmental data under different flows and by the development of an estuarine model to predict the effects of different flow regimes.

2. To develop a set of economic accounts and an economic water evaluation framework and associated tools, using the Little Swanport catchment as a case study, to assess the value of freshwater to the various users across the catchment, including upstream agriculture, estuarine shellfish farmers and fishers and for non-market goods and services.

Our research has shown that the profitability of both agriculture on land and aquaculture in the estuary is affected by changing freshwater flows. To assess the value of water to different users across a catchment we developed a generic water accounting framework and populated it with available data from the Little Swanport catchment as an example. We also developed an estuarine ecosystem model which we used along with field observations and nutrient budgeting to assess the value of freshwater flows to oyster production in the estuary.

During this study the catchment moved into a severe drought. This necessitated some revision to our research methods and we used the drought conditions to estimate the value of water to the different users across the catchment from the loss in production during drought years compared to normal rainfall years. This provided estimates of the economic value of water at two extreme points on a continuum.

Across the catchment the loss of income from wool production, fat lamb sales and beef production when rainfall was approximately 60% of a normal year was estimated to be $3,36 million, or approximately one-third of its normal state (cash crops were not included as there were insufficient data). This value was determined from the sum of preventative expenditure, replacement costs and loss of production incurred due to the drought. In the estuary the nutrient budget and ecosystem model predicted that the drought years of 2006 and 2007 would have led to a decrease in the nutrients in the estuary, and a subsequent decline in the productivity of phytoplankton, oysters and benthic microalgae. By comparison, in the two wet years (2004 and 2005) nitrogen budgeting indicated that the increase in oyster harvest was ~43 kg N or a 12% increase relative to the drought years 2006-07. This equated to a loss of approximately $500,000 in a severe drought year.

The loss in production in the estuary during the drought was largely due to a lowering of the growth rate of the oysters, and as a consequence they took longer to reach market size and condition. On land, however, many farmers were forced to destock and only keep essential breeding animals. Crops either failed or produced less than normal and were not sown due to lack of water storage. Thus, the recovery time after the drought is likely to be greater on agricultural farms, taking several years to improve grazing land and to restock, whereas in the estuary the recovery time is in the order of months. Recovery time also depends on the stocking density before the drought and whether the farmers were stocked to full capacity for good growing conditions or whether they maintained a lower stocking level which would provide a buffer during droughts.

In relation to environmental flows to the estuary, it is important to note that maintaining the low flows is most important. Ecosystem model simulations at different levels of base flows predicted that phytoplankton biomass, and consequently oyster growth, initially increases rapidly with base flow before the rate of increase slows to a steadier rate at higher flows. Therefore, there are greater benefits to the estuary per ML of river flow at low flow than at high flows. At low river flows primary producers have more time to take up the additional nutrient inputs from the river because the time to pass through the estuary is longer. In contrast, at higher flows, there is less time for biological uptake as the flushing time is shorter, and so the benefits are smaller per ML of river flow. The results of this study therefore support the cease to take requirements for low flows in the Water Management Plan for the catchment. However, the modelling predicted that the greatest benefits from river flow are achieved over the summer months because higher water temperatures significantly enhance the growth rates of phytoplankton and oysters.

An assessment of the implications of increased water that could be allocated for stock, domestic and irrigation purposes in the Water Management Plan (2006) from 3882 to 6084 ML per year was shown by modelling to be unlikely to have a significant impact on the estuary for average and dry years, but in very dry years, as recently experienced in 2007, there was a detectable effect of the full allocation, most notably in summer. However, given the uncertainty inherent in model simulations, the result should be treated with caution. The important message is that harvesting water during a very dry year is more likely to affect the estuary, especially during summer.

Although this research has centred on the Little Swanport catchment, the techniques developed are of relevance to many catchments across southern Australia. The biogeochemical model can be applied in other estuaries where there are sufficient local data, particularly on hydrodynamics. The nutrient budget process can also be used in other estuaries with relevant local nutrient data available. The water evaluation framework developed for the catchment provides a generic template for catchments to assess the value of water to different users across a catchment. Data requirements, survey methods and types of analyses, along with likely issues and potential difficulties to water accounting are discussed.

Outcomes achieved

As a result of the research conducted in Objective 1, significant new information is available on estuarine ecology and the impact of changing freshwater flow regimes on the health of an estuary and the commercial production of oysters. This information will underpin improved management of estuaries, including sustainable oyster production, which was an important planned outcome of the project. In particular, it will be used in the five-yearly review of the Water Management Plan for the Little Swanport catchment.

A template for a water evaluation framework for catchments has been developed to assist managers to value the different uses of water across a catchment. A detailed set of water accounts was prepared for the Little Swanport catchment as a case study. These results support the sustainable management of water resources in this and other catchments, which was a planned outcome.

The increased stakeholder and community awareness in the Little Swanport catchment of the environmental and economic benefits and costs of providing freshwater flows for primary production and for the environment is also an important outcome as this underpins improved water management.

Keywords

Water management, catchments, environmental flows, estuarine health, oyster aquaculture

Acknowledgments

First we wish to thank the people of the Little Swanport catchment, especially the Little Swanport Catchment Management Implementation Committee (LSPCMIC) for their continued hospitality, interest and support for the project.

A collaborative NRM South – Glamorgan Spring Bay Council project to 'Develop a Whole-of-Catchment Management Plan' for the Little Swanport catchment operated in close association with our project and we are grateful for the support and assistance of the Project Officer, Sandy Dunbabbin. Sandy provided much valuable information on the people and operation of the catchment and was often our first point of contact. Similarly, we sincerely thank Melanie Kelly, NRM Officer with Glamorgan Spring Bay Council and Secretary of the LSPCMIC, for her ongoing support and commitment to the project.

We are grateful to Oyster Bay Oysters for their logistical support, especially for providing boat transport during difficult weather, for providing oysters and grow-out facilities on their farm for our oyster growth rate trials, for regular sampling and analysis of phytoplankton and for allowing us to use their oyster processing facility to process our samples.

We would also like to thank John Hunter and Barry Gallagher for their advice on the development of the transport model. To Barry, the many long discussions on everything estuarine were invaluable and much appreciated. Many thanks to TAFI technical officer Sam Foster who made an enormous contribution to the field and laboratory components of the project. We also wish to thank the casual staff and students who contributed significantly to the field component, including Camille White and Ryuji Sakabe.

This project has been enhanced by funding provided to the Principal Investigator by the University of Tasmania for a Qualitative Marine Science Post Doctoral position, which provided an additional 18 months of salary and a small amount of operational funds to continue developing the model and collecting limited environmental data in Little Swanport (LSP) estuary.

An NRM–NAP-funded project awarded to the Tasmanian Department of Primary Industry and Water (DPIW) Water Assessment and Management Branch to develop holistic flow regimes for several catchments in Tasmania has provided additional funds for the collection of environmental data and research on the source and fate of nutrients in the LSP estuary.

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Background

The extraction of freshwater from rivers and bores for irrigation, industrial use, town water supplies etc is increasingly occurring across Australia, resulting in decreasing amounts of water reaching estuarine environments. Estuaries are particularly vulnerable to pollution because they are the downstream end of accumulated pollutants in a river system and the impact of these wastes on estuarine ecosystem health can be greatly exacerbated if flushing flow events are removed. Many state governments have responded or are in the process of responding by implementing management plans for sustainable water resource use, which attempt a whole-of-catchment approach to water management. However, although environmental flows in freshwater systems have been investigated for many years, the requirements for freshwater into estuaries to maintain estuarine health and shellfish aquaculture production are poorly understood. Also, the monetary value of water resources to different sectors across a catchment, in particular non-market ecosystem services, is poorly defined.

This project aimed to determine the freshwater flow regimes that are essential to the maintenance and/or enhancement of estuarine function, productivity and ecosystem health, using the Little Swanport (LSP) catchment in Tasmania as a case study (Figure 1). Little Swanport was selected for detailed investigation because of the strong stakeholder and community involvement in the development of a community-based Catchment Management Plan and Water Management Plan for the catchment. This information on freshwater flows is required to underpin sustainable use and management of water resources, and in particular to support Water Management Plans for catchments across Tasmania. It also investigated the economic value of freshwater flows to different users across the catchment, including to estuaries.

Farmers in the headwaters of the Little Swanport River and its tributaries have plans for expansion of agricultural production based on the extraction of greater quantities of water for irrigation. Numerous dams have been built in the past and several dam applications are currently pending State Government approval. Tradeoffs between water users and environmental flows are becoming increasingly common but also increasingly problematic in estuaries because of the poor knowledge base. This project, therefore, is important to primary producers by assisting shellfish aquaculturists and estuarine fishers to establish their need for freshwater in the estuary and agricultural farmers to assess their impact and reliance on freshwater.

The production of farmed shellfish is an important commercial activity in LSP – the oyster nursery produces approximately 70% of the spat for on-growing on farms in Tasmania and South Australia, and the oyster farms have an estimated gross return of \$31 500 per hectare per annum (Dyke & Dyke 2002). Many shellfish farmers in

Tasmania believe production of the most commonly grown species, the Pacific oyster *Crassostrea gigas*, is enhanced by freshwater flows into estuaries. This oyster is physiologically adapted to less than fully marine conditions, showing highest growth rates and survival at salinities of around 25 parts per thousand. Other commonly cited reasons for enhanced production are that inflows from rivers deliver nutrients to estuaries which support increased production of phytoplankton, the main food of oysters. However, the importance of estuarine freshwater flows to shellfish production has not been assessed in Tasmania and very little information is available from mainland Australia. Similar research from overseas has shown that heavy regulation of a catchment by dams has resulted in increased noxious algal blooms and decreased diatom blooms, which is correlated with low water discharges and decreased silicon delivery to the estuary (Rocha et al. 2002).

This project attempts to integrate social, economic and ecological investigations in the development of effective water management plans. To our knowledge, an economic evaluation of freshwater use including the value to estuarine fisheries and aquaculture has not been previously examined in Australia. Results from the ecological modelling are integrated within the socioeconomic study to examine the value of water usage between alternative users in the catchment and a generic economic evaluation framework has been developed. As demands on water continue to expand, an ability to make informed decisions is a growing challenge. However, assessing the value of non-income earning goods and services that are reliant on water resources with those that have a clear economic benefit (such as increased animal or crop production) has generally been fraught with difficulties. This project further develops the concept of ecosystem services and societal benefits from the environment, and how they can be recognised, valued and managed.

Consultation and previous research

As water management plans have been developed around Tasmania, the need for a better understanding of the role of freshwater flows in estuarine integrity has been increasingly recognised by stakeholders, especially State Government managers and stakeholders reliant on productive estuaries for their livelihood. As a consequence, a meeting was held in 2003 to develop a partnership-based project to examine the freshwater flow requirements for estuarine health and productivity. Although there was strong support for the project from a wide range of stakeholders, it took several years for funding from FRDC/LWA to become available. In the interim period this research commenced with short-term funding from several sources.

A collaborative project on developing holistic flow methods in the Little Swanport catchment, which was conducted by DPIWE Water Assessment and Planning Branch, commenced in late 2003, with funding from NAP (National Action Plan for Salinity and Water Quality). As a consequence, there was considerable urgency to commence collection of environmental data in the estuary at the same time as the NAP project, especially as the nutrient analysis of estuarine samples was to be funded by the NAP project. The collection of environmental data in the estuary commenced in January 2004 with TAFI core funding and this was further supported financially with a grant of

$25 000 from the DPIWE Water Development Branch. Funding for the following 12 months was provided by NHT/NRM South as a one year initial gap project. The research during these two years concentrated on monthly water quality sampling, measuring nutrients (TN, TP, ammonia, nitrate/nitrite, phosphate, silicate, iron), chlorophyll-*a*, phytoplankton and zooplankton biomass and identification of dominant species, temperature and salinity profiles through the estuary, dissolved oxygen, suspended solids and turbidity. Sampling fish communities in the estuary also commenced in early 2004, with intensive monthly sampling at the narrow entrance to the estuary and at the upstream end of saline water penetration using a combination of plankton, fyke and gill nets and beach seine. The results are presented in Crawford et al. (2006). A habitat map of the estuary including bathymetry, sediment particle size, benthic microalgal biomass and seagrass beds in the estuary was also completed and is available at:
<<http://www.utas.edu.au/tafi/seamap/Zoomify/mappage_hellfire_schouten.htm>>.
These data have formed the basis for the current FRDC/LWA project.

Extension of current FRDC/LWA project

After the FRDC/LWA project was approved, the 18-month salary funding was leveraged against a University of Tasmania Qualitative Marine Science Post Doctoral position, which provided an additional 18 months of salary and a small amount of operational funds to continue developing the model and collecting limited environmental data in LSP estuary.

At the same time, the postdoctoral fellow, Dr Jeff Ross, became a collaborating partner (as the estuarine expert) on an NRM NAP funded project awarded to the Tasmanian Department of Primary Industry and Water (DPIW) Water Assessment and Planning Branch to develop holistic flow regimes for several catchments in Tasmania. This project is working in two catchments with estuaries, the LSP and Ringarooma. Thus, additional environmental data are being collected and further research is being conducted on the source and fate of nutrients in the LSP estuary.

As a consequence, the project was granted a no-cost extension for 18 months, provided that the additional data from the NRM NAP project is included in the FRDC/LWA final report.

Need

The importance of quantifying the impacts of land-based anthropogenic activities on freshwater flows and consequential effects on downstream estuarine and coastal water environments has been increasingly recognised in recent years. Nevertheless, extraction of freshwater for agriculture, town water supplies etc is increasing in many rivers across Australia. The ecological effects on estuaries of changing flow regimes is largely unknown in Tasmania, and Australia generally, and there is an urgent need to quantify the freshwater flow requirements essential to estuarine health and aquaculture production. Similarly, there is limited information on the socioeconomic value of freshwater flows into estuaries. Consequently, there is a need to assess the economic efficiency of allocation of freshwater to land-based agricultural production as well as to estuarine-based shellfish farming and ecosystem goods and services.

These priority research needs have been identified in a number of R & D plans and strategies. The FRDC five-year plan called for a balanced mix of economic, environmental and social factors in making use of natural resources. High priority issues recognised by stakeholders in the Tasmanian Fisheries and Aquaculture five-year draft strategic plan for the Marine Environment 2004–2009 included:

- Integrated catchment management
- The determination of environmental flow regimes into estuaries
- Social and economic value of the environment – assessment of sectors.

At the Marine Environment Research Advisory Group meeting in 2004 one of the top priorities for research identified for the year was 'Catchment management and impact of land derived pollutants etc. on water quality and quantity, and environmental flows'.

The Tasmanian Natural Resources Framework 2002 identified Water Management and Management of the Coastal/Marine Environment as state priority issues. Important values listed were biodiversity, aquatic ecosystem health, irrigation for agricultural, aquaculture and fisheries production, and issues included environmental flow regimes and water allocation.

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Objective 1

Introduction

Freshwater is undisputedly one of world's most important, but limited, natural resources. The demand for freshwater resources is increasing as a result of increased human development and water use. As a consequence, there has been a general increase in the extraction of freshwater from rivers, streams, lakes and groundwater for agriculture, and for industrial and municipal uses (Valiela 2006). In the year 2000, approximately 14% of the flow of all the rivers in the world was used by people (Valiela 2006). To protect freshwater-dependent ecosystems from the negative effects of flow regulation, environmental flows are increasingly becoming an essential component of regulated flow regimes both in Australia (Arthington & Pusey 1993, 2003; ARMCANZ & ANZEC 1996) and overseas (Tharme 2003). Environmental flows in river ecosystems may be allocated for a number of purposes such as to restore connectivity between river reaches and flood plains, to alter bed morphology, to provide spawning cues for fish or to reduce disturbance such as salinisation or sedimentation.

Estuaries, one of the most biologically productive environments on earth, constitute the critical transition zone where freshwater from land drainage mixes with seawater (Kennish 2002). Although freshwater discharge, and the nutrients it delivers, has been recognised as contributing to the high productivity of estuaries, the freshwater needs of the downstream estuaries have rarely, until recently, been considered. Surprisingly, the perception still remains among many that 'water going to the sea is wasted' (Whitfield & Wooldridge 1994; Rosenburg et al. 1995). Perhaps one of the most alarming examples of the importance of freshwater flows for estuaries and coastal environments comes from the effects of the Aswan Dam on the coastal Mediterranean ecosystem (Aleem 1972). Constructed in 1965 on the Nile River to store all the river water above the Aswan to generate hydro-electricity and for the irrigation of land, the Aswan Dam led to a massive decline in the nutrients that reached the coast. The result was lowered phytoplankton production on the coast and a concomitant decline in commercial fish catches. Catches of sardines, a plankton-feeding fish, declined from 15 000 t in the year before the dam was completed to 550 t two years after the completion of the dam, and catches of prawns (shrimp) in the Egyptian sector of the Mediterranean were halved (8000 down to 4000 t) (Aleem 1972). Reduced freshwater flows to estuaries may not only lead to a decline in the nutrients essential for phytoplankton production, but may also alter the ratio of the various nutrients (Officer & Ryther 1980). Because silica may be in or absorbed by particles, the trapping of sediment particles behind dams selectively traps silica, whereas nitrogen travels mainly in its oxidised inorganic form, nitrate, which travels freely dissolved in water. This alteration of the silica to nitrogen ratio promotes the growth of flagellates which may form noxious blooms at the expense of diatoms (e.g. Rocha et al. 2002).

In Australia, the importance of environmental flows to estuaries is increasingly being recognised; many state governments are responding by implementing management plans for sustainable water resource use, which attempt a whole-of-catchment approach to water management. Despite this recognition, there are still very few published studies that have actually demonstrated the benefits of environmental flows to estuaries and of those studies that have, the majority have focused on the benefits to commercial and recreational estuarine and coastal fisheries (e.g. Loneragan & Bunn 1999; Robins et al. 2005; Halliday et al. 2008). Unfortunately, doubt and a lack of information about the effectiveness of environmental flows in delivering ecological benefits can hinder environmental water allocations where there are competing water uses. The importance of documenting the influence of freshwater flow to Australian estuaries is further exacerbated because they are likely to behave differently to estuaries in other parts of the world (with the likely exception of South Africa). Moreover, climate change is predicted to alter the amount of freshwater available through changes in rainfall patterns and associated run-off (Eyre 1998; Hughes et al. 2003). The Australian climate is highly variable and many Australian estuaries lack consistent seasonal or inter-annual patterns of freshwater flow, with several Australian rivers having the most variable flow on earth (Puckridge et al. 1998). This variability can be seen in the average coefficient of variation of annual flow (C_v) which is more than twice as high in Australian (C_v = 0.70) and South African (C_v = 0.78) rivers compared with North American (C_v = 0.35) and European (C_v = 0.28) rivers (Finlayson & McMahon 1988; Eyre 1998)

Little Swanport estuary case study

The aim of this study was to identify the freshwater flow regimes that are essential to the maintenance and/or enhancement of the health and productivity of the Little Swanport estuary in south-eastern Tasmania. Little Swanport (
Figure 1) was selected for detailed investigation because of the strong stakeholder and community involvement in the development of a water management plan for the catchment (DPIW 2006). Importantly, the information gained in this study is required to underpin the specific environmental objectives and statuary requirements of the plan to 'protect flow regimes to maintain estuarine processes dependent on freshwater inputs'. The need for this study was further highlighted following an appeal lodged by oyster (*Crassostrea gigas*) growers in the estuary with the Resource Management and Planning Appeal Tribunal against plans to dam 1280 ML of water in the upper reaches of the Little Swanport River for agriculture. Tradeoffs between water users and environmental flows are becoming increasingly common and problematic in estuaries because of the poor knowledge base.

The specific aim of this study was to assess the importance of environmental flows to the estuary, which included gaining an improved understanding of the ecosystem dynamics of Little Swanport estuary and examining the role of oyster aquaculture in estuarine dynamics. Three approaches were used to address these aims (1) field observations, (2) an observation-based nutrient budget and (3) a dynamic ecosystem model.

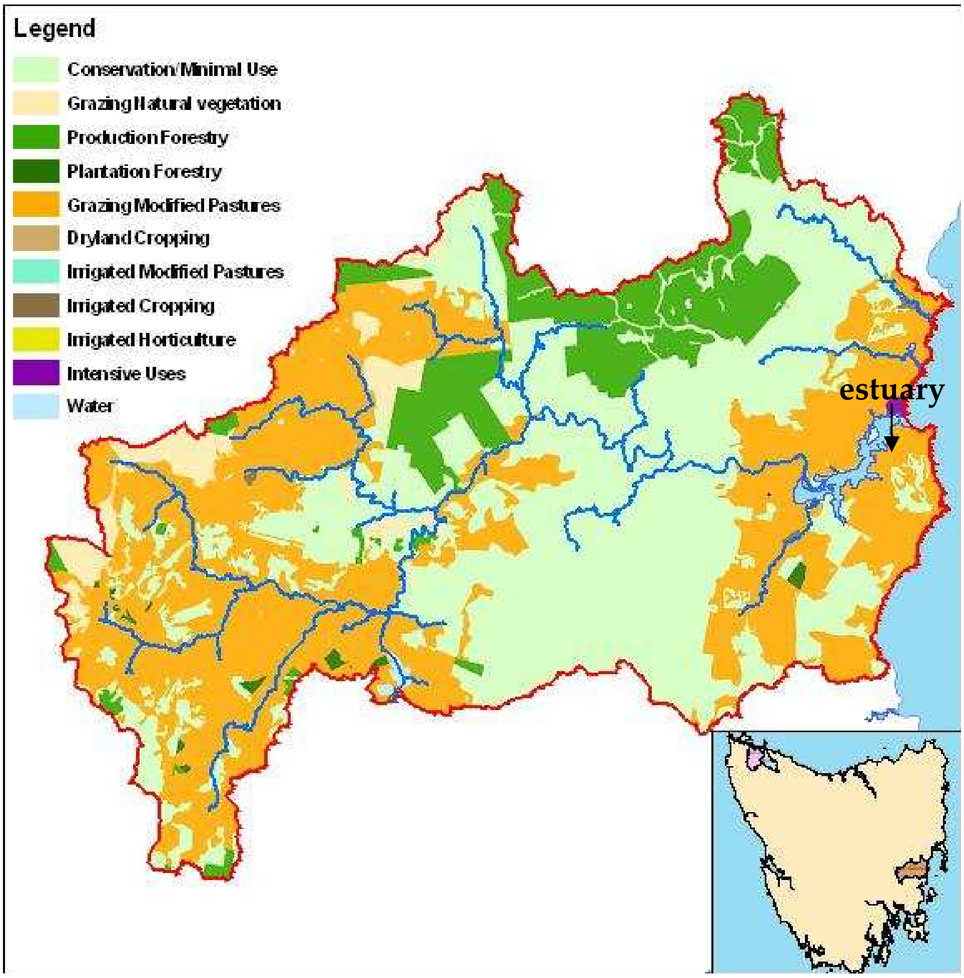


Figure 1 **Little Swanport catchment, land uses and estuary (Drenen 2003).**

Methods

Field observations

The most recent field study of the Little Swanport estuary carried out by Crawford et al. (2006) collected monthly samples at sites throughout the estuary between January 2004 and January 2005. Measurements included water column nutrients, chlorophyll-*a*, dissolved oxygen, salinity, phytoplankton, zooplankton and oyster growth. This work demonstrated that freshwater flows had a significant effect on salinity, turbidity, dissolved oxygen and nutrient levels in the estuary. However, monthly sampling didn't provide the temporal resolution necessary to detect potential flow-on effects on the biology (e.g. phytoplankton and zooplankton dynamics, oyster growth). To gain an improved understanding of the temporal dynamics of the estuary, including the response to freshwater flow, samples were collected weekly (chlorophyll-*a*), fortnightly (nutrients and zooplankton) and bimonthly (oysters) between March 2006 and June 2008 at a site in the lower estuary where the majority of oysters are farmed (see Figure 2).

Duplicate water samples were collected from ~20 cm below the surface for analysis of ammonia, total oxidised inorganic nitrogen (nitrite + nitrate), phosphate and silicate. Nutrient analysis was conducted by Analytical Services Tasmania (AST) using the American Public Health Association (APHA) Method 4500 on a Lachat Instrument auto analyser. Duplicate water samples for chlorophyll-*a* were collected using an integrated sampler consisting of 3 m long, 2.5 cm diameter tubing which sampled the entire water column to a depth of ~3 m. The sample was then filtered through a Whatman GF/F glass microfibre filter, and the filtrate wrapped in aluminium foil and frozen. Chlorophyll-*a* concentrations were measured spectrometrically following 90% acetone extraction (Strickland & Parsons 1972). To ensure consistency with the units used in the ecosystem model (mg Nitrogen m^{-3}), chlorophyll-*a* was converted to nitrogen using a ratio of 7 mg N mg Chl-a^{-1} (see Murray & Parslow 1997)

Zooplankton was sampled using a 100 µm mesh, single conical plankton net that was 3 m long and 0.6 m in diameter, towed ~20–30 m behind a boat. An ocean flow meter suspended in the mouth of the net was used to calculate sample volume. Samples were immediately preserved using 4% buffered formalin in seawater and later sorted in a Bogorov tray under a dissecting microscope. When zooplankton abundances were very high, samples were split using a Folsom splitter. Zooplankton abundance was converted to biomass in milligrams of nitrogen per cubic metre (mg N m^{-3}) using existing information on the average nitrogen content of the major families (K Swadling, *unpub data*).

To gain an improved understanding of the dynamics of oyster growth in the estuary, particularly the response to environmental flows, the growth and change in condition of oysters was measured bimonthly. The start samples consisted of 280 oysters, approximately 50–60 mm in length, selected from the farm, with 240 placed back on the farm; 60 per basket in each of two units (each unit has two baskets). The remaining 40 oysters were measured in the laboratory to provide an estimate of initial size and condition. After two months all of the oysters were collected and 20 oysters from each basket were measured in the laboratory. This cycle was repeated with a new batch of oysters every two months. To estimate oyster growth, shell length, width and depth were measured to the nearest millimetre using Vernier calipers and the whole live weight of the oysters was measured to the nearest milligram. To calculate oyster condition, tissue dry weight (60°C for 48 h) and shucked shell dry weight (60°C for 48 h) were measured and used to estimate the Crosby Gale Index (1990):

$$\text{Crosby and Gale Index (1990)} = \frac{\text{tissue dry weight (g) x 1000}}{\text{internal shell cavity capacity(g)}}$$

where internal shell cavity capacity = whole live weight (g) – dry shell weight (g).

Nutrient budget

The simplest approach to describing and understanding the nutrient dynamics of a coastal water body is an observation-based nutrient budget: identifying and quantifying the important fluxes into (including freshwater flows) and out of the water body. The difference between the inputs and outputs indicates whether the estuary is a net sink or a net source for the nutrient of interest. To ensure a common and consistent budgeting approach that can produce outputs at a local scale and can be integrated into larger scale regional and global synthesis, the Land Ocean Interactions in the Coastal Zone (LOICZ) program produced guidelines for the collection of empirical data and estimation of budgets (Gordon et al. 1996; www.loicz.org). We describe these methods as applied to the Little Swanport estuary below, approximated as a single well mixed box. The budget described here is for nitrogen, given widespread evidence that nitrogen is the key limiting nutrient in coastal marine ecosystems (e.g. Boynton et al. 1982). Essentially the same procedure has been followed for phosphate and silicate. To help understand the influence of oyster aquaculture in Little Swanport, the role of oysters was also factored into the estuary's nitrogen budget. Table 1 lists the important reservoirs, internal fluxes and external inputs and outputs that are elements of the nitrogen budget constructed for Little Swanport.

Figure 2 Aerial photograph of the Little Swanport estuary showing the oyster farms, the field site used in this study, oyster nursery, river entrance and channel (photo by Dr F J Neira, TAFI).

Reservoirs

To begin constructing the nitrogen budget, we required estimates of the nitrogen levels in phytoplankton (P), dissolved inorganic nitrogen (DIN), detritus (D) and oyster (O) reservoirs within the Little Swanport estuary. To formulate the nitrogen budget, all quantities are expressed as an equivalent nitrogen concentration per unit volume, and later converted into tonnes of nitrogen per year for the annual budgets. DIN was determined by summing the direct measurements of nitrate, nitrite and ammonia concentrations. P was determined primarily from chlorophyll-*a* observations, converted to nitrogen using a ratio of 7 mg N mg Chl-a^{-1} (Murray & Parslow 1997). In instances when chlorophyll-*a* data didn't exist but suspended particulate matter (SPM) did, we used the relationship between chlorophyll-*a* nitrogen and SPM nitrogen concentrations (0.12% based on C:N analysis) measured during this study to estimate P. D was estimated as the difference between the amount of nitrogen in the SPM and the amount of nitrogen in the phytoplankton. This equated on average to a 50:50 split between phytoplankton nitrogen and detrital nitrogen. Because SPM and chlorophyll-*a* wase often not measured concurrently, we have assumed a 50:50 split for all budget calculations.

The biomass of oysters on the farms in Little Swanport is based on an average of 2.15 million oysters on the Oyster Bay Oysters lease and 8 million oysters on the Shellfish Culture lease at any one time during the year. Oysters on the Oyster Bay Oysters lease are split evenly between small (20–35 mm), medium (35–50 mm) and large (50–80 mm) size classes, and oysters on the Shellfish Culture lease include 60% very small (4–20 mm), 12.5% small, 12.5% medium and 15% large.

Table 1 Elements of the nitrogen budget in the Little Swanport

Symbol	Description
Reservoirs	
P	Phytoplankton
DIN	Dissolved Inorganic Nitrogen
D	Detritus
O	Oysters
Oyster fluxes	
P→O	Ingestion
D→O	Ingestion
O→D	Biodeposition
O→Harvest	Oyster Harvest
O→DIN	Excretion
External fluxes	
River	River loads
Ocean	Ocean exchange

To convert the size class data into biomass (as dry tissue weight), the relationship between shell length and dry tissue weight (DTW) calculated for oysters from Pipeclay Lagoon was taken from Crawford et al (1996):

$$Log(L) = 0.39 \cdot Log(DTW) + 4.00$$

where L is shell length in millimetres and DTW is dry tissue weight in grams. Note that the oyster data collected in Little Swanport during 2006–08 is consistent with this relationship (Figure 3). An average nitrogen content of 10.79% of the oyster dry tissue weight was estimated via C:N analysis of oyster tissue samples from Little Swanport.

Externals fluxes

River loads

River inputs are based on river level data collected by the Water Resources Division, Department of Primary Industries, Water and Environment, Tasmania (DPIWE), at gauging station 2235 which is located approximately 1 km upstream of the upper limit of the estuary. The gauge's river height – flow rating table was then used to generate daily river flow (megalitres per day; ML/day). River load estimates were made using relationships between water quality parameters and river flow measurements at the gauge site collected by DPIWE as part of their state-wide baseline monitoring network (www.dpiw.tas.gov.au/waterquality). Physical and chemical data are collected during monthly visits to the site and additional samples have also been collected during floods using automated sampling equipment. The relationship between dissolved inorganic nitrogen (DIN) and river flow was poor (n = 51, $R^2 = 0.32$). In contrast there was a stronger relationship between total nitrogen (TN) and river flow (n = 93, $R^2 = 0.59$; Figure 4). The relationship between TN and DIN (n = 70, $R^2 = 0.65$; Figure 4) was then used to calculate flow-weighted concentrations, and hence loads of DIN. Note that in the later correlation, 20 extra data points that had been previously excluded from the first two correlations, because there was no corresponding river flow measurement, were used to increase the power of the analysis. The equations that describe the correlations used to estimate loads are as follows:

1. $$Log(TN) = \left(\frac{Log(RiverFlow) - 6.9144}{5.0813} \right)$$

2. $$DIN = 0.0099 \cdot e^{2.4604 \cdot TN}$$

Having established these relationships, the daily flow time series was transformed into a daily time series of total nitrogen concentrations using equation 1, and concomitantly into a daily time series of dissolved inorganic nitrogen concentrations using equation 2. However, given the aggregated nature of the data and the form of the modelled relationships in Figure 4, the following limits were applied: if river flow < 10 ML/day then TN = 0.4 mg N L^{-1} and if TN >1.55 mg N L^{-1} then DIN = 0.45 mg N L^{-1}. Figure 5 shows the modelled relationship between river flow and DIN with the limits applied. To provide an estimate of the instantaneous load for each parameter, the transferred time series concentration data were multiplied by the discharge volume for that period.

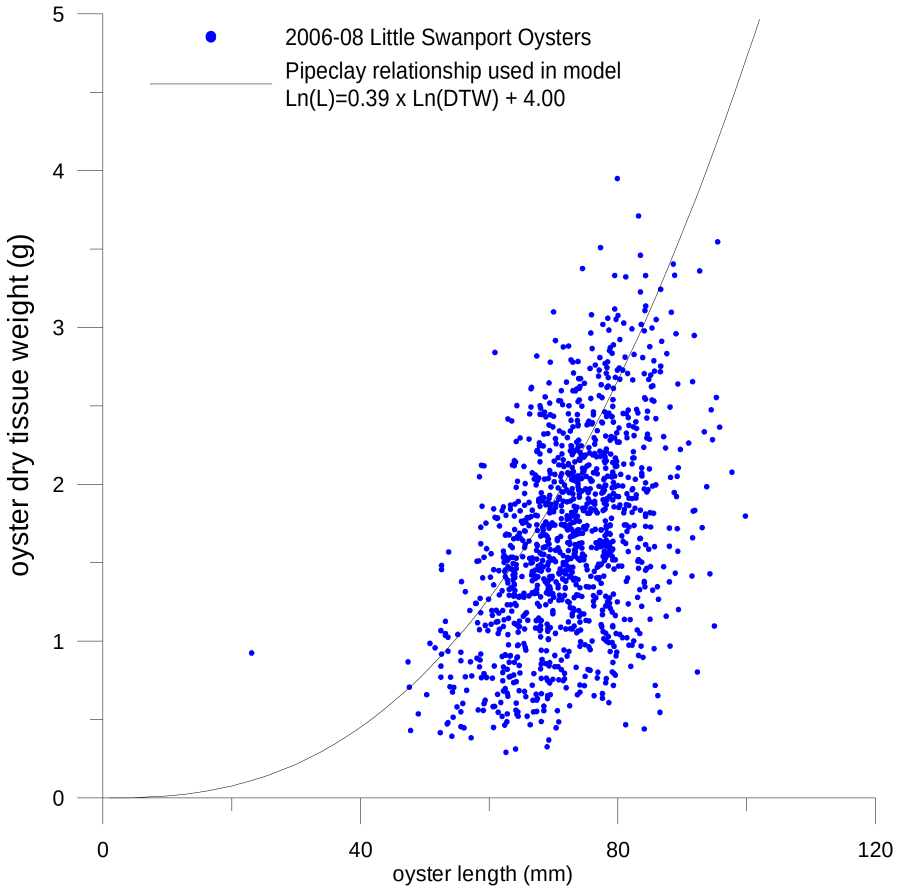


Figure 3 Relationship between shell length and dry tissue weight calculated for oysters from Pipeclay Lagoon by Crawford et al. (1996) used in the nutrient budget and ecosystem model (solid line). The blue dots represent oyster length and weight data collected in Little Swanport during 2006–08.

To calculate loads of detritus, SPM measured in the river by DPIWE was first converted into units of nitrogen using direct measurements of the nitrogen content of water column detritus in the river (0.07% N). Note that it was assumed that any living freshwater phytoplankton cells wouldn't survive in the estuarine environment, and thus all of the organic matter in the river water was detritus. There was no relationship between SPM nitrogen and river flow. A constant freshwater concentration of 8 mg N L^{-1} based on the average concentration measured by Crawford et al. (2006) was adopted and multiplied by the discharge volume for that period to calculate loads.

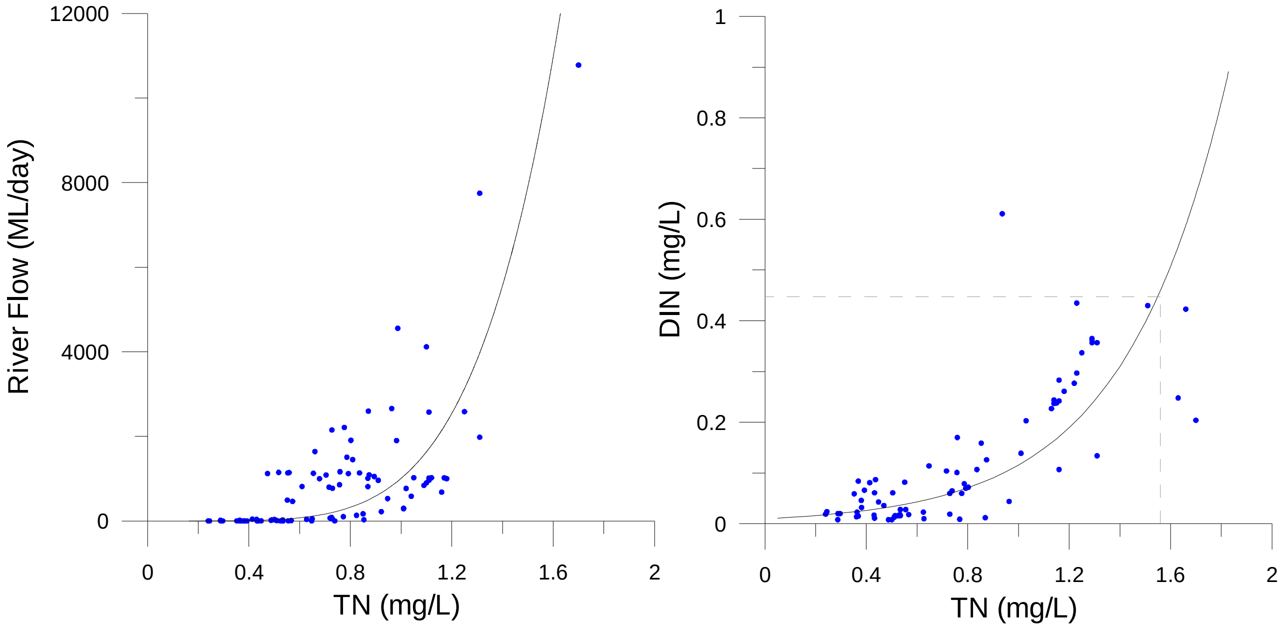


Figure 4 Relationship between total nitrogen (TN mg/L) and river flow (ML/day), and between total nitrogen (TN mg/L) and dissolved inorganic nitrogen (DIN mg/L) at Little Swanport gauging station 2235. The dashed line shows the limit for DIN; i.e. if TN > 1.55 mg N L^{-1} then DIN = 0.45 mg N L^{-1}.

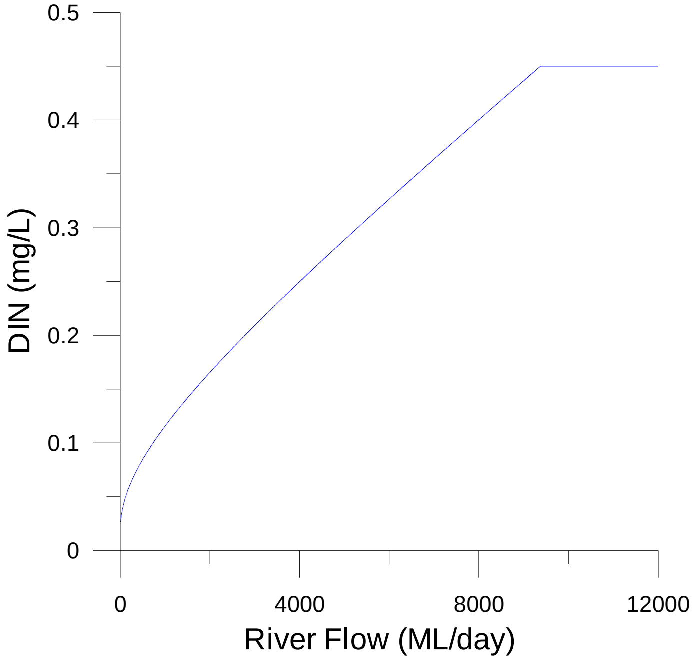


Figure 5 Modelled relationship between dissolved inorganic nitrogen (DIN mg/L) and river flow (ML/day) used to calculate river loads to the estuary in budget calculations and the ecosystem box model.

Ocean exchange

Whenever possible, we have used field data from the most recent study (Crawford et al. 1996) for setting ocean boundary conditions for DIN, P and D. Figure 6 shows the modelled seasonal cycle for DIN and the distribution of data points on which it is based. For P (measured as chlorophyll-*a*) there were very few data points and no apparent seasonal patterns, so we have adopted a constant ocean boundary condition of 7 mg N m^{-3} which is the average concentration measured by Crawford et al. (2006).

To calculate the amount of detrital nitrogen at the ocean station, we used the same method described above for calculating detrital nitrogen in the estuary and river, but with the percentage nitrogen at 0.01% in ocean SPM based on C:N analysis. Comparison of SPM nitrogen and P nitrogen indicated that there was negligible detrital N, and thus we adopted a constant boundary condition of 0 mg N m^{-3}.

To quantify the flux of DIN, P and D across the estuary–ocean boundary, the amount of water exchange across the boundary is required. In systems for which freshwater inflow and salinity data are available and if there is a difference in salinity between the system of interest and adjacent waters, a simple water and salt budget can be used to describe the 'hydrographic budget' for a system (e.g. the inputs of water to the system and the outputs of water from the system). In this study, the fraction of freshwater method outlined by Dyer (1973) was used to calculate the amount of time that freshwater spends in the system, commonly referred to as the 'flushing time' (τ_f) of the estuary. With the Little Swanport Estuary approximated as a single well mixed box, flushing time of the estuary is defined as:

$$\tau_f = \frac{\textit{freshwater volume}}{\textit{freshwater input}} = \frac{\left(\dfrac{S_{oc} - S_{est}}{S_{oc}}\right) \cdot V}{Q_f}$$

Where S_{oc} = ocean salinity, S_{est} = estuarine salinity, V = estuarine volume and Q_f = freshwater input.

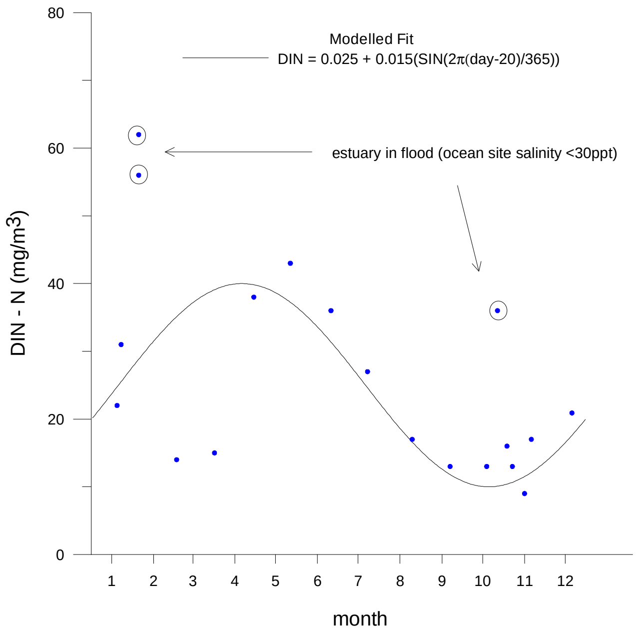


Figure 6 Modelled seasonal cycle (solid line) of dissolved inorganic nitrogen at the ocean boundary station used in the budget calculations based on field observations (blue dots).

Ocean salinity (S_{oc}) was measured at the ocean boundary site. Estuarine salinity (S_{est}) was depth and volume weighted because the estuary becomes stratified during high river flows. This was achieved by restricting the analysis to dates when salinity depth profiles (1 m intervals) were measured at the three main estuarine monitoring sites (2, 3 and 4; see Figure 7). The estuary was split into three segments, with boundaries equidistant between each monitoring site; the volume in each segment in one-metre depth intervals was used to convert the salinity measurements into a segment- and depth-weighted salinity measurement for the whole estuary. Estuarine volume (V) and the volume in each segment were calculated using a three-dimensional representation of the estuary created by ARC View GIS 3.2a from the bathymetry map of Crawford et al. (1996) (Figure 7).

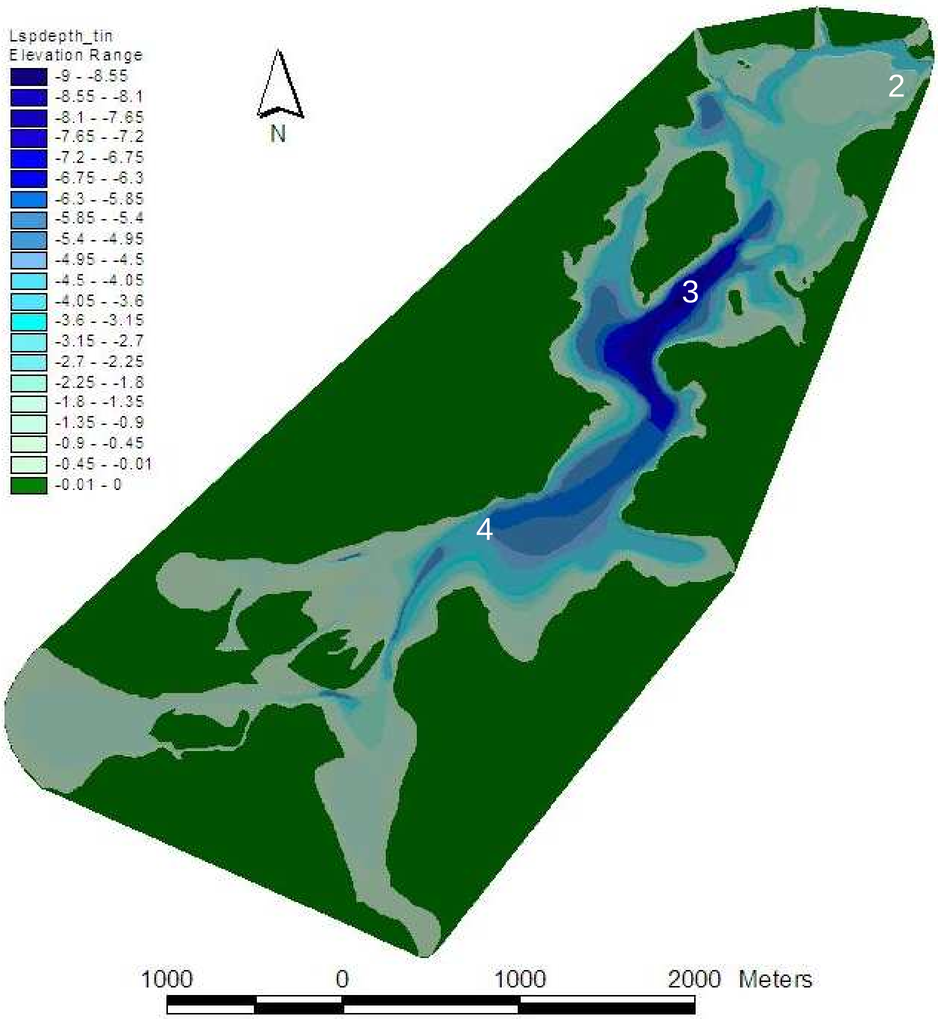


Figure 7 Bathymetry model of the Little Swanport estuary created in ARC View GIS 3.2a, showing the three main sampling sites (2, 3 and 4).

Daily freshwater input (Q_f) was generated as described above. When river flow is not constant, which is generally true under most time scales of interest, the appropriate time period to average for use in the calculation is problematic. While this method has been used widely in many estuaries, some investigators use the river flow on the actual date(s) of observation (e.g. Eyre & Twigg 1997); some use flow averaged over a fixed number of days prior to the field data (e.g. Atkinson et al. 1978); while others use monthly or seasonally averaged flow (Pilson 1995). In this study, the date-specific method of Alber & Sheldon (1999) is used in which it is assumed that the appropriate time period over which to average discharge is equivalent to the flushing time. Although this approach is still technically a steady state calculation, it improves flushing time estimates (Alber & Sheldon 1999). To calculate flushing times, an iterative process was used in which the flushing time calculation was initialised with the discharge measured on the date of interest and the resultant calculated flushing time (in days) was compared with the discharge period for the calculation (in the initial case, one day). The calculation was then worked backwards, incorporating the previous days measured discharge into the mean until the calculated flushing time was within one day of the discharge period used.

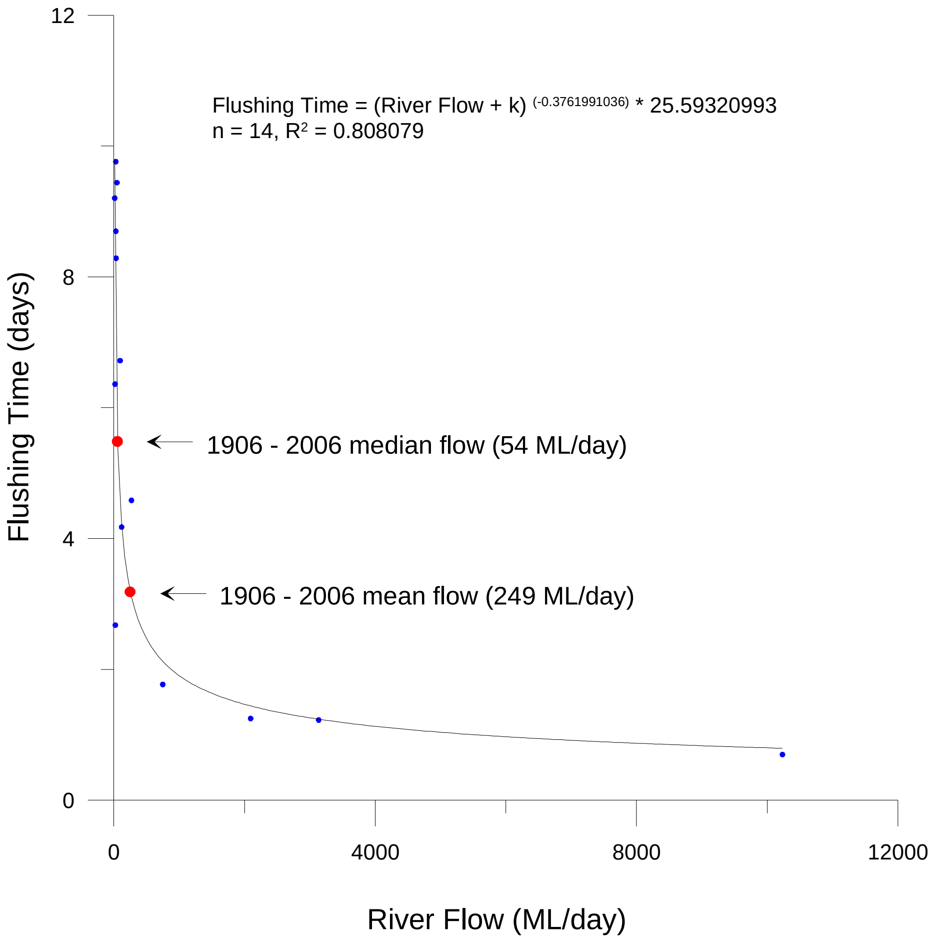


Figure 8 The relationship between flushing time and river flow for the Little Swanport estuary. The blue dots show the calculated flushing times for field measurements and the solid line represents the negative power function fitted to this data. The red dots represent the mean and median flows of the daily flow time series over 100 years of current water use generated from a water balance model established for the catchment by Sinclair Knight Merz (SKM 2004).

The relationship between flushing time and river flow for the Little Swanport estuary is a power function: as river flow increases, flushing time decreases quickly, but at high river flows flushing time is relatively stable (Figure 8). In the context of estuarine hydrodynamics, the most probable explanation for this relationship is best described in three phases. When river flow is absent or negligible, tidal energy is the major driver of physical circulation and exchange with the ocean. As river flow increases, the flow of freshwater causes a characteristic circulation pattern (commonly referred to as 'estuarine circulation') in which the freshwater entering at the head of the estuary creates a near surface flow of lighter freshwater out of the estuary and a compensating deep flow of saltier water up towards the head of the estuary (see Lazier & Mann 2006 for a detailed explanation of 'estuarine circulation'). This buoyancy-driven circulation enhances exchange with the ocean, and the magnitude of this exchange increases with river flow. However, when river flow is sufficiently large, it dominates exchange with the ocean at the mouth of the estuary, and there is little influence of tidal energy and no compensatory deeper flow of saltier water from the ocean to the estuary. For the Little Swanport estuary, it appears that estuarine circulation breaks down and river flow dominates physical exchange with the ocean when river flow is around 500–1000 ML per day.

It is important to note that because the relationship between flushing time and river flow is a power function, it is undefined at zero river flow. The relationship was modified to include a constant k, which defines the flushing time at zero river flow. Because the fraction of freshwater technique relies on a quantifiable salinity difference between the estuary and ocean, it doesn't work very well when there is no river flow. As an alternative, the mixing equations outlined by Yanagi (2000) were used to give a first approximation of the mixing exchange in the absence of river flow. Governed by the dispersion process and the magnitude of the horizontal dispersion coefficient D_H (m^2s^{-1}), mixing across the ocean boundary is estimated from the current shear and the diffusivity normal to the current shear by the following equation (from Taylor 1953). In the case of dominant vertical shear, the Little Swanport estuary (LSP) is classified as a 'narrow and deep estuarine system' according to the criteria that an estuary is narrow and deep if L/W>2 and W/H <500):

$$D_H = \frac{1}{120}\left(\frac{H^4}{Kv}\right)\left(\frac{U}{H}\right)^2$$

where H (in metres) is the average depth of the ocean boundary of the system; W (in metres) is the width of the estuary mouth; L (in metres) is the distance from the centre of the system to its mouth; U (in metres per day) is the residual flow velocity at the surface layer of the open boundary; K_v is the vertical diffusivity. Assuming a K_v of approximately 8 in a vertically well mixed system and with D_H (in square metres per day) and U (square metres per day) rescaled the equation becomes:

$$D_H \approx \frac{1}{1000}(HU)^2$$

where H ~2 m and U ~33 000 m^2 day^{-1} (Crawford et al., 1996) in LSP and D_H is ~ 4357267 m^2 day^{-1}. The horizontal dispersion coefficient can then be used to approximate the mixing volume (V_x) and flushing time in the absence of river flow using the following equations:

$$V_x = D_H\left(\frac{A}{F}\right) \text{ and } \tau_f = \frac{V}{V_x}$$

where A denotes the cross-section area of the open boundary (~290 m^2 in LSP) and F is the distance between the centre of the system and observation point for oceanic salinity (~4000 m in LSP). This equates to a flushing time of ~25 days in the absence of river flow with the constant k = 1 in the flushing time river flow equation. Given the importance of river flow as a determinant of flushing time and hence water exchange across the mouth of the estuary, this relationship is fundamental to calculating budgets in systems such as Little Swanport that have highly variable river flow. To calculate the export of material from the estuary to the ocean, the flushing time is defined such that the time-dependent rate of reduction of a conservative tracer with a concentration C introduced into the estuary from the river would be:

$$\frac{dC}{dt} = \frac{C}{\tau_f}$$

The solution to this equation is an exponential decay equation,

$$C = C_{initial}\, e^{-\frac{t}{\tau_f}}$$

which says that at time $t = \tau_f$, the initial tracer concentration C_{init} would be reduced to e^{-1} of its initial amount. In terms of the mass exported this can be written as,

mass exported = $C_{estuary}.(1-e^{-\frac{t}{\tau_f}}).V$

If the oceanic water mixing across the estuarine boundary also contains the conservative tracer, the mass imported will be,

mass imported = $C_{ocean}.(1-e^{-\frac{t}{\tau_f}}).V \cdot \left(1-\frac{Q_f}{V}\right)$

Note that the mass imported is reduced by the fraction $(1-\frac{Q_f}{V})$, which represents the mass of the conservative tracer in the residual amount of water that must flow out of the system to balance the freshwater inflow and keep the estuarine volume constant.

Oysters

The amount of phytoplankton and detrital nitrogen consumed by oysters depends on the rate at which oysters filter water (i.e. their clearance rate) and the nitrogen content of the suspended particulate matter (SPM) in the water column. Although clearance rates (litres per hour) are likely to increase with the size of oyster, Crawford et al. (1996) found no relationship with size when expressed as clearance rate per dry tissue weight. The clearance rate for oysters used was 43.16 L (g dry weight)$^{-1}$ day^{-1}. This is within the range of values observed for *Crassostrea gigas* in oyster farms in Tasmania by Crawford et al. (1996).

To allow for a direct comparison with budgets produced by the ecosystem model, in which the rate parameters are temperature dependent, oyster clearance rates in the budget were also temperature corrected using the method described in the ecosystem model section. The amount of nitrogen ingested was calculated by multiplying the clearance rate by the SPM concentration by the nitrogen content of SPM. An average nitrogen content of 0.12% of SPM was estimated via C:N analysis of SPM samples collected in Little Swanport. This was multiplied by the estimated biomass of oysters in the estuary to calculate the total amount of nitrogen removed. To estimate how much of the nitrogen ingested is derived from phytoplankton and detritus, the proportion of nitrogen in SPM associated with phytoplankton was estimated from chlorophyll-*a* samples assuming nitrogen to chlorophyll-*a* ratio of 7:1. The amount of nitrogen associated with detritus was calculated as the difference between the amount of nitrogen in the SPM and the amount of nitrogen in the phytoplankton. For the period in which both chlorophyll-*a* and SPM were measured concurrently, this equated on average to a 50:50 split between phytoplankton nitrogen and detrital nitrogen.

Assimilation efficiency, the proportion of food ingested that is actually used for growth, was given a value of 0.5 for phytoplankton, based on the experiments of Crawford et al. (1996). Because filter feeders such as oysters often assimilate detritus much less efficiently than they do phytoplankton (e.g. Wilson et al. 1993), the assimilation efficiency for detritus was given a value of 0.25. We then assume that 0.25 of the phytoplankton and detrital nitrogen assimilated is excreted as DIN. The amount of nitrogen produced as faeces (i.e. detritus) by the oysters is the difference between the nitrogen ingested and the nitrogen assimilated.

Stoichiometric estimates of key biological processes

One procedure for gaining insight into the processes leading to the nonconservative fluxes of carbon, nitrogen and phosphorus is to examine the stoichiometric linkages between the fluxes. An underlying assumption of this approach is that chemical stoichiometry of the organic matter involved in these processes can be approximated. In plankton-based systems, organic matter is likely to have the Redfield carbon nitrogen phosphorus (CNP) ratio of 106:16:1. However, in systems such as Little Swanport with a large area of seagrass, this ratio may not be an accurate representation. A detailed survey of the carbon nitrogen (CN) ratio of water column particulate matter, sediment particulate matter and seagrass in Little Swanport in summer 2007 found ratios of 7.1, 11.1 and 21.7 respectively. This suggests that seagrass detritus is making a substantial contribution to the organic matter pool in the sediments. Following a review of datasets for over 27 seagrass species, Duarte (1990) reported a CNP ratio of 474:21:1. For Little Swanport we will assume an intermediate CNP ratio of 193:17.4:1.

Net ecosystem metabolism

Because organic matter production takes up nutrients, while respiration liberates nutrients, whether the system is a source or sink of carbon, nitrogen and phosphorus can be used to identify the difference between primary production and respiration. This difference (p - r) is often called 'net ecosystem metabolism'. Because the nitrogen cycle is more complicated than the phosphorus and carbon cycles, as a consequence of the side reactions of denitrification and nitrogen fixation, carbon and phosphorus (which move more simply between dissolved inorganic forms and organic matter) are used to estimate net ecosystem metabolism. Therefore, it is assumed that net ecosystem metabolism accounts for the nonconservative flux of dissolved inorganic phosphorus ΔDIP calculated in the budget such that:

$$[p - r] = -\Delta DIP \times (C/P)_{part}$$

where $(C/P)_{part}$ is the C:P ratio of the reacting particulate matter. In the LOICZ budgeting procedure, Gordon et al. (1996) acknowledge that this is still a very simplified interpretation of the phosphorus cycle given reactions involving sorption-desorption and precipitation-dissolution, but suggest that these side reactions for phosphorus are generally less quantitatively important than for N and C, in terms of net nonconservative fluxes, and that in general ΔDIP is likely to be a useful general proxy for net ecosystem metabolism. These results will be compared to direct measurements (via ΔO_2) of production and respiration made over vegetated (seagrass) and un-vegetated habitats at four sites in the estuary using core incubations under *in situ* conditions (NAP TEFlows project *unpub data*).

Net nitrogen fixation minus denitrification

An equation similar to that for calculating net ecosystem metabolism can be written to describe the expected amount of dissolved inorganic nitrogen (ΔDIN_{exp}) taken up and released with the dissolved phosphorus flux:

$$\Delta DIN_{exp} = \Delta DIP \times (N/P)_{part}$$

where $(N/P)_{part}$ is the N:P ratio of the reacting particulate matter. Any difference between ΔDIN_{obs} and ΔDIN_{exp} is an indicator of processes other than organic metabolism which alter dissolved inorganic nitrogen fluxes. Nitrogen fixation and denitrification are likely to be important pathways for nonconservative nitrogen fluxes in many marine systems, so this difference is taken as a measure of net nitrogen fixation minus denitrification ([nfix-denit]):

$$[nfix - denit] = \Delta DIN_{obs} - \Delta DIN_{exp}$$

Whilst it is preferable to have data on ΔDON and ΔDOP in this equation to allow for possible conversions between organic and inorganic forms of these materials, these data are not available, and it can only be assumed that the nonconservative fluxes of these dissolved organic materials is small.

Ecosystem box model

As we discussed in the previous section, construction of an observation-based nitrogen budget is the simplest approach to quantifying the important fluxes into and out of the system; however, in systems with highly episodic river flow such as Little Swanport, field sampling regimes are normally not conducted at high enough frequency to resolve the discharge variation and the estuarine responses that they may cause (see Webster et al. 2000). To resolve variations in estuarine responses that can arise from daily variation in river discharge, an ecosystem box model was developed for the Little Swanport estuary. The model was developed in STELLA (isee systems); systems thinking software designed to allow for the easy construction and simulation of dynamic environments.

Model applications

In the first instance, the model was used to calculate annual pools and fluxes for comparison with the results of the observation-based nutrient budget, but also to provide estimates of the other pools and fluxes that could not be directly estimated. The model was then used to examine the role the river plays in the functioning of the estuary, and the likely impacts of changes in river flow to the estuary. The model was applied to the Little Swanport estuary under three scenarios:

1. Although the estuarine response to river flow is no doubt likely to vary depending on the magnitude, frequency and history of river flow events, in the first instance, the model was used to examine the role of base river flow to the estuary. Model simulations were carried out for a two-year period, and the outputs compared across simulations with different base flows, ranging from 0 to 200 ML day^{-1} year^{-1}. This will also help us assess the relevance of the cease to take flow periods (≤ 7.6 ML per day, November to April and ≤ 9.5 ML per day, May to October) in the plan that are ostensibly based on the environmental water requirements of the Little Swanport River rather than the estuary.
2. Over the course of this study (and the preceding study by Crawford et al. (1996)) the catchment has moved into a drought. In 2004 and 2005, total flow into the estuary was ~31 251 and 75 258 ML respectively, compared with 1238 and 4258 ML in 2006 and 2007 respectively. To understand the impact of the drought on the estuary, and to help gain a better understanding of the influence of natural variability in river flow, the model was run for the 2004–2007 period.
3. As part of the Little Swanport Water Management Plan (DPIW 2006) the catchment allocation limit was increased from 3882 to 6084 ML per year. To assess the impact of the increased allocation on the estuary, the model simulations using hydrographs of the flow regime under the previous allocation limit were compared with model simulations using hydrographs under the plan. This was repeated in a dry year and an average year (Figure 24).

Model structure

The basic structure of the ecosystem model was based largely on the ecosystem model developed for the Port Phillip Bay Environmental Study (PPBES; Murray & Parslow

1997; 1999). While complex three-dimensional hydrodynamic models are often implemented to define the transport and mixing between spatial compartments of the ecosystem, such as in the PPBES, the Little Swanport estuary appears to be well mixed and was treated as a single well mixed compartment. The transport of water column properties across the estuary – ocean boundary was calculated based on the river flow versus flushing time model described above.

This model was written as a nitrogen model because (as explained in the nitrogen budget) there is widespread evidence that nitrogen is the key limiting nutrient in coastal marine ecosystems (e.g. Howarth & Marino 2006). Therefore, all state variables in the model are represented as an equivalent nitrogen concentration per unit volume or per unit area (see Table 2 for a list of state variables). Because other nutrients can also play a major role in phytoplankton and nitrogen dynamics, such as silica that is required by diatoms, the model has the ability to carry other nutrients by assuming that the composition of organic matter (living and non-living) follows the fixed empirical ratios defined by Redfield (planktonic plants) and Atkinson (benthic plants). The model structure and behaviour was verified by comparison with well documented empirical responses to altered forcing functions, such as nutrient loads (e.g. phytoplankton biomass response).

Table 2 List of the state variables, with symbols and units

State Variable	Symbol	Units
Phytoplankton	P	mg N m^{-3}
Zooplankton	Z	mg N m^{-3}
Microphytobenthos	MPB	mg N m^{-2}
Seagrass	SG	mg N m^{-2}
Oysters	O	mg N m^{-3}
Labile Detritus	LD	mg N m^{-3}
Refractory Detritus	RD	mg N m^{-3}
Disolved Inorganic Nitrogen	DIN	mg N m^{-3}
Disolved Organic Nitrogen	DON	mg N m^{-3}
Light	I	W m^{-2}
Temperature	T	^{o}C

The model includes three sub models: a water column model, an epibenthic model and a sediment model (Figure 9). The water column model is based on a nitrogen-phytoplankton-zooplankton-detritus model or so-called NPZD model (e.g. Fasham 1990). The basic NPZD model has been extended to include oysters (O) that are suspended in the water column on oyster racks. Detritus (non-living organic matter) has also been divided into labile (DL) and refractory (DR) particulate detritus, and refractory dissolved organic matter (DON). Nitrogen, as DIN, DON, DL and DR enters the water column model via river discharge, and together with P and Z, DIN, DON, DL and DR are also exchanged with the ocean across the estuary mouth. Internally, DIN is taken up during phytoplankton growth; phytoplankton is consumed by zooplankton; detritus is generated through zooplankton and phytoplankton mortality and grazing; and DIN is generated through zooplankton respiration or mineralisation of detritus (either directly or via DON). Oysters consume phytoplankton and detritus, and generate DIN and detritus through excretion and faecal production, respectively.

Oyster biomass is held constant throughout the year based on industry estimates, with oyster growth removed during harvest. The biomass value takes into account industry estimates of mortality.

The epibenthic model represents benthic plants (seagrass (SG) and microphytobenthos (MPB)) located at the sediment–water-column boundary. The benthic plants grow subject to light and nutrient conditions at the sediment surface. In the model they are assumed to take up nutrients from the sediments, although in reality they are likely to take up some of their nutrients from the water column. The sediment model adopts the semi-empirical representation of sediment processes used by Murray & Parslow (1997) for the PPBES. This includes the bacterial breakdown of particulate and dissolved organic matter derived from the water column and sediments to dissolved inorganic nitrogen (DIN). The subsequent rates of nitrification and denitrification are represented implicitly, with their relative importance dependent on the overall sediment respiration rate.

Model processes

The model describes the flow of nitrogen through primary producers, consumers, detritus, and dissolved inorganic and organic pools. A summary of the local rate of change equations for each of the state variables in the model is presented in Table 3. A more detailed description of the mathematical formulation of each of these processes is presented in Appendix 3A. The model was run on a daily time step and equations are integrated in time using a 4th order Runge-Kutta integrator (see Appendix 3B for the assessment of numerical stability).

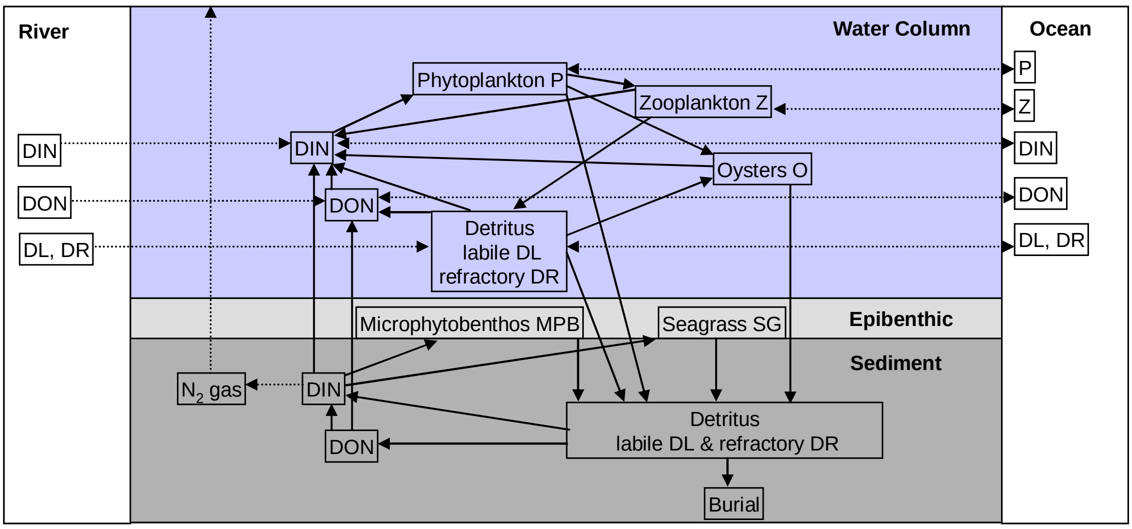


Figure 9 Flow of nitrogen through the ecosystem box model of the Little Swanport estuary.

Model forcing

The model is driven by inputs of nutrients from the river, by exchanges of nutrients, phytoplankton and zooplankton at the boundary with the ocean, and by seasonal variation in temperature and solar irradiance. River flow and associated nutrient loads were estimated on a daily time step as described above for the nutrient budget.

Similarly, ocean boundary conditions and exchanges across the ocean boundary were calculated on a daily time step as described above for the budget.

Temperature

Water temperature (*T*) in coastal water bodies is often approximated by an empirical seasonal cycle (e.g. Murray & Parslow 1999). When calibrated against monthly temperature observations in the Little Swanport estuary, the following model provided a good fit (Figure 10):

$$T = 14.5 + 5.8 \cdot \cos\cdot\left(2 \cdot \pi \cdot \frac{[day - 31]}{365}\right)$$

Table 3 Model equations. The terms and formulations of these equations are explained in Appendix A

Water column sub-model

Dissolved inorganic nitrogen

dDIN/dt = import_oceanDIN + riverDINload + DLremin + Zexcret + Oexcret + DRremin + DONrem + sedprodDIN + NitrLoss - Pgrowth – export_oceanDIN

Phytoplankton

dP/dt = Pgrowth + import_oceanP - export_oceanP - ZgrazeP - OgrazeP - Psink

Zooplankton

dZ/dt = ZgrazeP + import_oceanZ - ZprodDL - Zexcret - export_oceanZ

Oysters

dO/dt = OgrazeP + OgrazeDL - Oexcret - OprodDL

Labile detritus

dDL/dt = ZprodDL + import_oceanDL + riverDLload - DLremin - DLprodDR - DLsolnDON - OgrazeDL - export_oceanDL - DLsink

Refractory detritis

dDR/dt = DLprodDR+ riverDRload – DRremin - DRsolnDON - DRsink

Dissolved organic nitrogen

dDON/dt= DLsolnDON + DRsolnDON + import_oceanDON + riverDONload – export_oceanDON - DONrem

Sediment sub-model

Dissolved inorganic nitrogen

dDIN/dt = DLremin + DONremin + DRremin - Nitrification - SGgrowth - MPBgrowth - sedprodDIN

Labile detritus

dDL/dt = OprodDL + Pmort + DLsink + SGmort + MPBmort - DLprodDR- DLremin - DLsolnDON

Refractory detritus

dDR/dt = DLprodDR+ DRsink - DRsolnDON - DRremin - DRburial

Dissolved organic nitrogen

dDON/dt = DRsolnDON + DLsolnDON - DONremin

Nitrate

dNO_3/dt = Nitrification - Denitrification - NitrLoss

Phytoplankton

dP/dt = Psink - Pmort

Epibenthic sub-model

Microphytobenthos

dMPB/dt = MPBgrowth - MPBmort

Seagrass

dSG/dt = SGgrowth- SGmort

A number of the ecological processes are temperature dependent. The rate parameters in the model are all specified for a temperature of 15°C. To capture the temperature dependence, at each time step, the rate parameters have been multiplied by:

$$Tcorr = Q_{10}^{\left(\frac{ET-Tref}{10}\right)}$$

All rate parameters (i.e. those with units involving time: per day) are corrected in this way using a fixed value of Q_{10}, except RO and RD, the parameters controlling the shape of the denitrification relationship.

Light

The dataset of total daily global solar exposure derived from satellite data by the Bureau of Meteorology (BOM) for Swansea was incomplete, and as such, solar radiation at Little Swanport was simulated by calibration of the following formula by Ryan & Harleman (1973) against the existing data for Swansea:

$$I(n) = (a\cos\zeta - b)\cdot\left(1 - 0.65\cdot C^2\right)$$

where the zenith angle, ζ represents the position of the sun (see Fennel & Neumann (2004) for calculation), C is the fraction of sky covered by clouds (recorded at Swansea by BOM), and a and b are parameters that were estimated on the satellite data. With a complete data set for cloud cover, total daily solar radiation could be estimated on a daily time step.

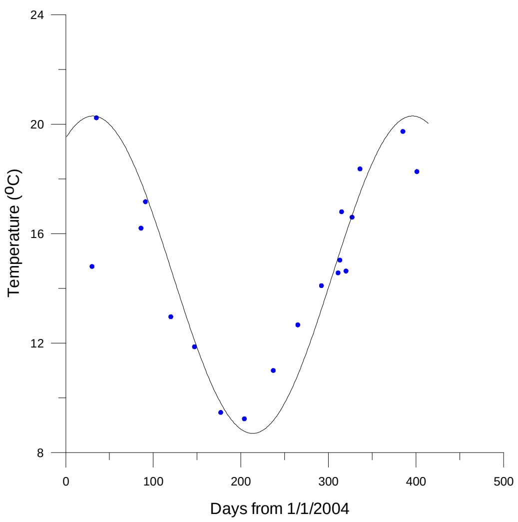


Figure 10 Water temperatures recorded in the Little Swanport estuary, and the empirical seasonal model.

In the model, the proportion of surface light (total daily average solar irradiance) available as photosynthetically available radiation (PAR) is assumed to be 43% (Fasham et al. 1990). PAR at the bottom of a layer of water, I_{bot} (mol photon m^{-2}, s^{-1}), is calculated as:

$$I_{bot} = I_{top} e^{-K_d \cdot dz}$$

and the mean light intensity over the layer as:

$$I_{aver} = \frac{\left(I_{top} - I_{bot}\right)}{K_d \cdot dz}$$

where I_{top} is the PAR at the top of the layer (mol photon m^{-2}, s^{-1}), dz is the thickness of the layer [metres], and K_d is the total attenuation coefficient of the water [per metre] given by the sum of each attenuating component in the water:

$$K_d = k_w + k_{DON}.\text{DON} + k_{DL}.(\text{DL} + \text{DR}) + k_P.(\text{P}) + k_{IS}.(\text{IS})$$

Here, k_W represents the background attenuation coefficient of seawater, k_{DON}, k_{DL} and k_P represent the nitrogen-specific attenuation coefficients for modelled DON, detritus and phytoplankton respectively, and k_{IS} is the attenuation coefficient due to inorganic suspended sediment. Although the model doesn't currently include sediment resuspension, by assuming a constant background value for suspended inorganic sediments (based on observations) of 25.46 g m^{-3} the effect of inorganic sediments delivered from the river on light attenuation is included.

Initial conditions

The state variables in the model were given reasonable values from field studies in the Little Swanport estuary (LSP; Crawford et al. 1996; Mitchell 2001; Murphy et al. 2003; Mount et al. 2005; Crawford et al. 2006). For seagrass, biomass (mg N m^{-2}) was based on mapped seagrass coverage and biomass (Mount et al. 2005) and an average nitrogen content of 2.18% for seagrass leaves in LSP (unpub data). Zooplankton biomass (mg N m^{-3}) was based on species/family abundance data collected by Crawford et al. (2006) and the average nitrogen content of the major families (K Swadling, *unpub data*). Phytoplankton measured as chlorophyll-*a* and dissolved inorganic nitrogen was based on average concentrations in LSP (excluding periods of flood); chlorophyll-*a* was converted to nitrogen using a ratio of 7 mg N mg Chl-a^{-1}. Dissolved organic nitrogen concentration was based on measurements in LSP by Potts (2005). Detrital nitrogen was estimated from particulate organic matter (POM) measurements and an average nitrogen content of 0.12% for water column detritus and 0.39% for sediment detritus in LSP (*unpub data*). We then assumed that 10% of this material was refractory. Sediment DIN and DON were given reasonable values from the literature (Murray & Parslow 1997).

The model was then run for a period of five years to allow the model to reach steady state before commencing the model simulations. The values at the end of this 'spin up' were used as the initial conditions for the model.

Model calibration

There are 42 biological parameters used in the model (Table 4). Calibration of these parameters and the forcing functions described above was carried out step-wise. Initially, parameter values were based on the values (and ranges) used by Murray &

Parslow (1997) in the ecosystem model developed for the Port Phillip Bay Environmental Study because of the similar temperature and light regimes and pelagic and benthic communities in Port Phillip Bay and Little Swanport. The parameters used for oysters are based on direct estimates from process studies carried out in Tasmanian estuaries (including Little Swanport) in the mid 1990s on *Crassostrea gigas* (Crawford 1996).

Prior to calibrating the model against field observations from Little Swanport, the dependence of model behaviour on specific parameters and forcing functions, particularly those with the greatest degree of uncertainty in their estimation, was examined. A detailed description of the sensitivity analysis is presented in Appendix 3C. The parameter values and forcing functions were then constrained by calibration of the model against observations from the Little Swanport estuary. The model was initially calibrated against field data collected between January 2004 and April 2005 by Crawford et al. 2006. However, due to a lack of parameters for extensive model calibration during 2004, a second calibration was carried out using the field observations collected in the first half of this study (March 2006 to July 2007). During calibration, the model parameters and forcing functions were altered step-wise in a series of numerical simulations until satisfactory agreement between predictions and observations (including observed temporal variation) in the major parameters measured in the field program (water column dissolved nitrogen concentration, phytoplankton and zooplankton biomass, and oyster growth) was obtained. A detailed description of the calibration procedure and results are presented in Appendix 3D.

Table 4 List of model parameters, and initial values with symbols and units.

Parameter	Description	Value	Units
	Light attenuation coefficients		
kw	Background attenuation for seawater	0.05	m^{-1}
kDOM	Dissolved organic matter	0.0007	m^2 (mg N)$^{-1}$
kP	Phytoplankton	0.0035	m^2 (mg N)$^{-1}$
kDL	Detritus (DL and DR)	0.0038	m^2 (mg N)$^{-1}$
kIS	Inorganic sediments	0.04	m^2 (g dry wt)$^{-1}$
kPAR	Proportion of solar radiation that is PAR	0.43	
	Light saturation intensity		
kI P	Phytoplankton	10	W m^{-2}
kI SG	Seagrass	10	W m^{-2}
kI MPB	Microphytobenthos	3	W m^{-2}
	Nutrient half-saturation constant for growth		
kN P	Phytoplankton	15	mg N m^{-3}
kN SG	Seagrass	5	mg N m^{-3}
kN MPB	Microphytobenthos	200	mg N m^{-3}
	Maximum growth rates		
mum P	Phytoplankton	1.2	d^{-1}
mum Z	Zooplankton	1.4	d^{-1}
mum SG	Seagrass	0.1	d^{-1}
mum MPB	Microphytobenthos	0.1	d^{-1}
mum O	Oysters	0.01	d^{-1}
SGmax	Maximum seagrass biomass	2000	mg N m^{-2}
	maximum clearance rates		
C Z	Zooplankton	0.12	m^3 (mg N)$^{-1}$ d^{-1}
C O	Oysters	0.00015	m^3 (mg N)$^{-1}$ d^{-1}
	Growth efficiency		
E Z	Zooplankton	0.5	
E O	Oysters	0.4	
	Linear mortality		
mL P	Phytoplankton	0.14	d^{-1}
mL Z	Zooplankton	0	d^{-1}
mL SG	Seagrass	0.005	d^{-1}
mS SG	Seagrass (due to overgrowth)	0.0003	d^{-1}

	Quadratic mortality		
mQ MPB	Microphytobenthos	0.00002	d^{-1} (mg N $m^2)^{-1}$
mQ Z	Zooplankton	0.1	d^{-1} (mg N $m^3)^{-1}$
	Detrital production		
FDG Z	Proportion of zooplankton growth inefficiency lost to detritus	0.25	
FDM Z	Proportion of zooplankton mortality lost to detritus	0.25	
	Detrital breakdown		
r DL	Breakdown rate of labile detritus	0.1	d^{-1}
r DR	Breakdown rate of refractory detritus	0.0036	d^{-1}
r DOM	Breakdown rate of dissolved organic matter	0.00176	d^{-1}
FDR DL	Proportion of labile detritus converted to refractory detritus	0.2	
FDOM D	Proportion of refractory detritus that breaks down to DOM	0.05	
	Denitrification		
RO	Sediment net respiration rate at which nitrification = 0	200	mg N m^{-2} d^{-1}
RD	Sediment net respiration rate of denitrifcation maximum	20	mg N m^{-2} d^{-1}
Dmax	Maximum efficiency of the removal of N by nitrification floowed by denitrification	0.7	
	Temperature		
Q10	Temperature coefficient for rate parameters	1.8	
	Sinking rates		
wP	Phytoplankton	0.3	m d^{-1}
wDLR	Labile and refactory detritus	0.5	m d^{-1}
wIS	Inorganic sediments	0.5	m d^{-1}

Model validation

To determine whether the parameters and forcing functions found by the calibration adequately represent the real values in the system, the model output was compared against field data collected in the second part of this study (1 July 2007 – 1 July 2008; Figure 11). According to the cost function (see Appendix 3D for details) which gives an indication of the quality of fit between the model and the field data, the fit was classed as very good (i.e. $C < 1$ standard deviation) for all four variables: oyster growth ($C = 0.26$), phytoplankton biomass ($C = 0.11$), zooplankton biomass ($C = 0.24$) and water column DIN concentration ($C = 0.74$). On closer inspection, final parameterisation of the model captures the longer term average growth rates for oysters well, but struggles to capture the shorter term monthly variation. For phytoplankton and zooplankton biomass the model tracks the seasonally variability observed in the field very well. The field observations of water column DIN were quite variable, with no clear seasonal pattern, and as such it is not surprising that the model fit for DIN wasn't as good. However, the winter peaks predicted by the model do correspond very well with the observed nitrate concentrations. Some of the difference between model predictions and the field observations is almost certainly due to spatial variability in Little Swanport such that a single measurement may not always be an accurate representation of the average concentration/biomass in the estuary at a given time.

It must be emphasised that the range of conditions during the validation and calibration periods were similar, particularly in regard to river flow, and thus the good fit during the validation period confirms the model behaviour under periods of low river flow. Ideally, it would be preferable to validate the model against observations obtained from a period in which other river conditions prevail from those in the period of data collection used for the calibration. Nonetheless, in the absence of this data, the model can still be used as a management tool for predicting estuarine response to different river flow scenarios. As more data becomes available under different river flow conditions, this model will be refined further, ensuring greater certainty in predictions.

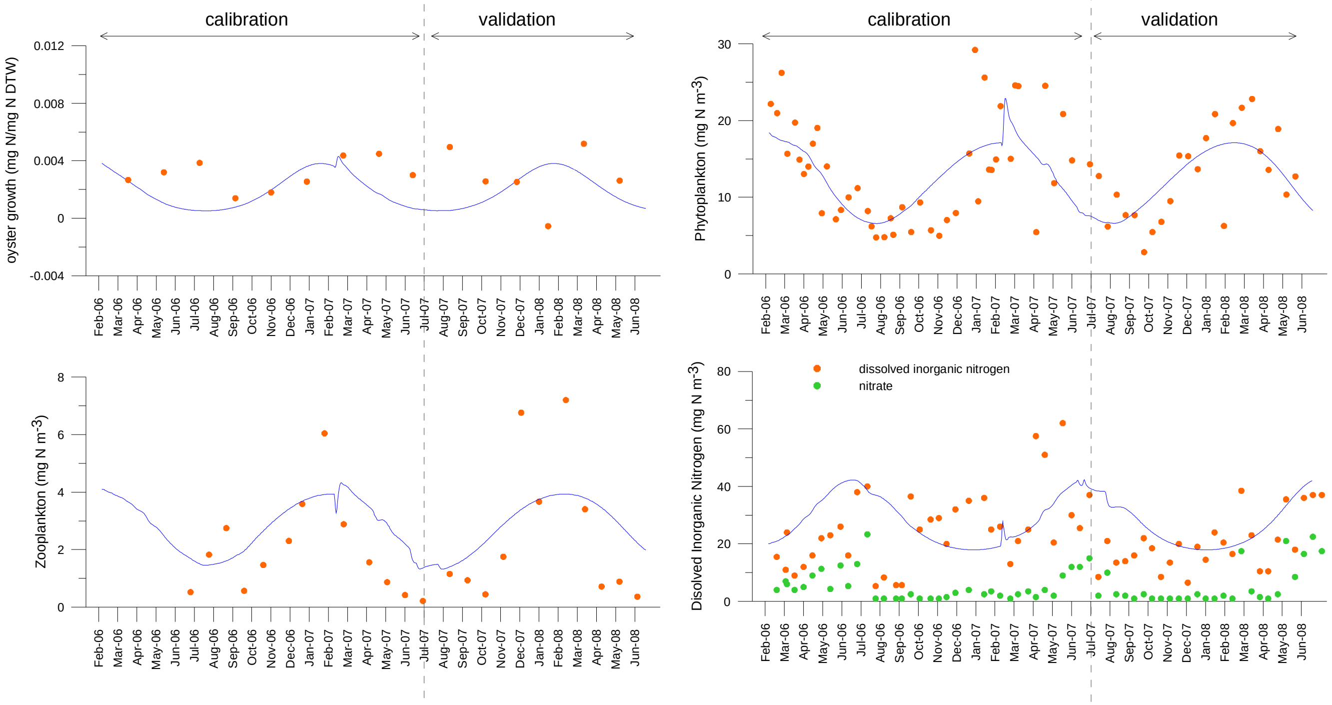


Figure 11 Comparison of model outputs (lines) using the parameters and forcing functions determined at the end of the calibration phase with field observations (points).

Results and discussion

Field observations

With the exception of a few very small flow events in early to mid 2007 there was virtually no river flow into the estuary during the study period (Figure 12). Whilst this clearly limited our ability to collect empirical evidence on the effects of river flow on estuarine dynamics, it provided an opportunity to understand how the estuary functions when river inputs are negligible. Dissolved inorganic nitrogen (DIN) concentrations varied considerably over the two-year period, with no clear seasonal patterns (Figure 12). However, in terms of the major constituents of DIN – ammonia and nitrate – ammonia largely tracked and was responsible for the pattern in DIN concentrations, but nitrate displayed a distinct seasonal pattern with concentrations increasing to 10–20 mg N m^{-3} in the middle of each winter from a very low background concentration of <4 mg N m^{-3}. This reflects a similar pattern seen in the ocean outside the estuary, and as such, the ocean may be the source of the winter nitrates observed in the estuary.

The elevated nitrate concentrations on the east coast of Tasmania in winter are due to the influence of nutrient-rich sub-Antarctic waters. In contrast, concentrations are lower between autumn and spring due to the influence of nutrient-poor East Australian Current (EAC) water and increased biological activity (Harris et al. 1987; Clementon et al. 1989). Phytoplankton, measured as chlorophyll-*a* also showed a distinct seasonal pattern, but with concentration peaking in late summer before declining to a minimum in late winter–spring (Figure 12). A very similar seasonal pattern was recorded by Brown & McCausland (1999) during fortnightly sampling between 1992 and 1997 further up the estuary at the oyster nursery (see Figure 2 for location). Interestingly, in the current study the maximum phytoplankton biomass occurred just before rather than after the nitrate peaks, indicating that the nitrate peaks may be due to the senescence and subsequent remineralisation of the dead plankton rather than nitrate imported from the ocean. Zooplankton biomass also peaked in summer, but with shorter-lived peaks in early to late summer. The increase in zooplankton biomass appeared to be slightly later and out of phase with phytoplankton as we might expect if the zooplankton are consuming the phytoplankton. However, the zooplankton peak was much shorter lived than the phytoplankton, raising the possibility of top-down control of the zooplankton biomass by higher order consumers such as fish.

The seasonal patterns observed for phytoplankton and zooplankton could be due to internal processes in the estuary or oceanic exchange. In the mid 1980s Harris et al. (1987) recorded higher chlorophyll *a* concentrations from spring through to autumn at a station off Maria Island, consistent with the general pattern observed using satellite-derived chlorophyll-*a* data for the adjacent coast during the course of this study (Figure 30). Similarly, Clementson et al. (1989) recorded the lowest biomass of zooplankton in winter each year at a station in south-eastern Tasmania. Ultimately, to understand the relative importance of internal processes and oceanic exchange, more detailed information on the hydrodynamics, internal nutrient fluxes and the species composition of phytoplankton and zooplankton inside and outside the estuary is required. Notwithstanding the need for more empirical data, the ecosystem model results discussed below indicate that the seasonal variability for phytoplankton and zooplankton is largely due to internal processes.

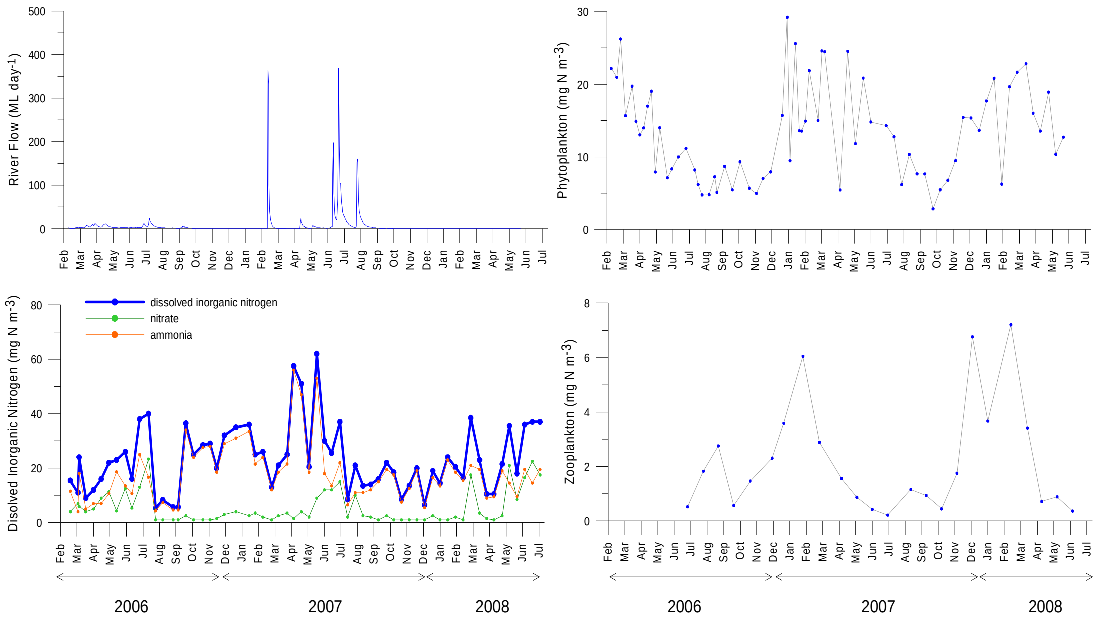


Figure 12 Time series plots of river flow, dissolved inorganic nitrogen, ammonia, nitrate and the biomass of phytoplankton and zooplankton expressed in mg N m^{-3}.

For the other measured dissolved inorganic nutrients that have the potential to limit primary production in the estuary – silicate and phosphate – there were no clear seasonal patterns (Figure 13). However, silicate for the most part was at concentrations below analytical detection limits, restricting our ability to identify seasonal patterns and whether diatom growth was limited. To identify whether nitrogen or phosphate concentrations may be limiting phytoplankton growth, the ratio of dissolved inorganic nitrogen to phosphate was compared to the Redfield ratio 16:1 and with few exceptions the ratio fell below 10, indicating that biomass development may be nitrogen limited (Figure 13).

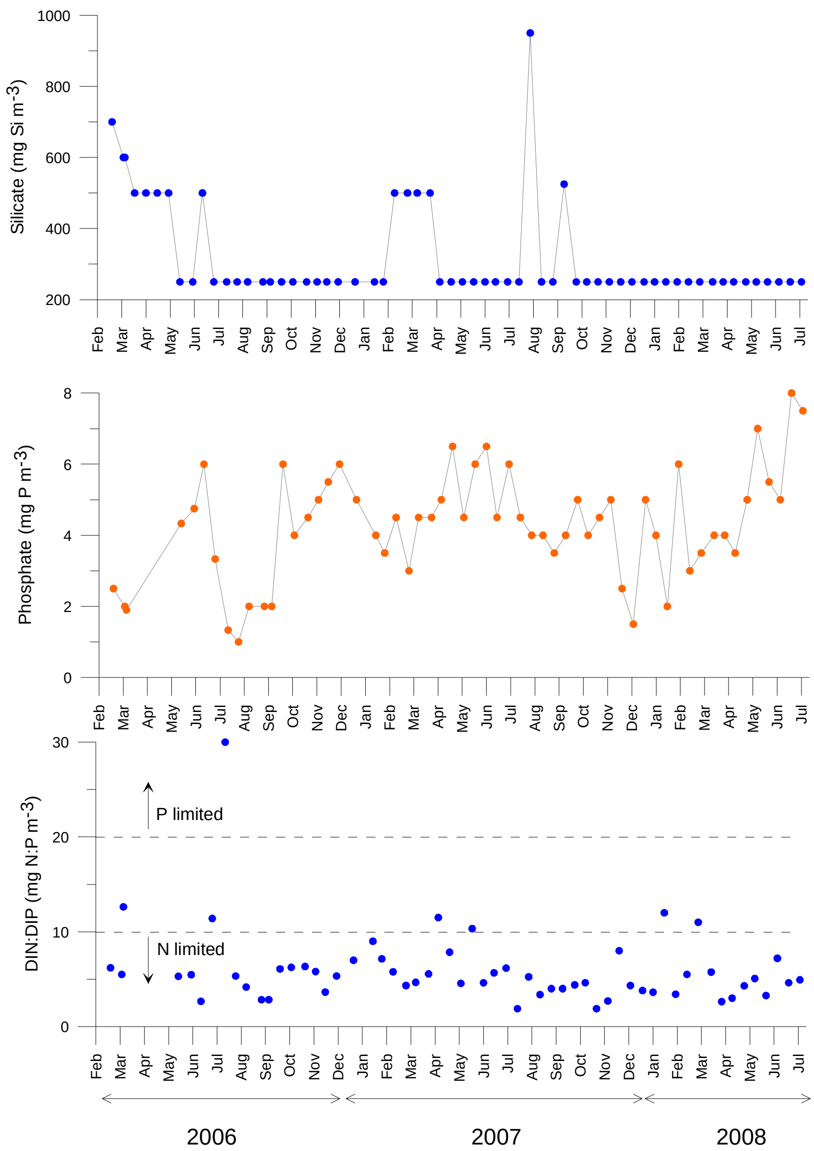


Figure 13 Time series of silicate, phosphate and the DIN:DIP ratio. If the DIN:DIP ratio falls below 10:1, biomass development may be nitrogen limited, and if a ratio of >20:1 occurs, phosphorus limitation may occur. Note: the detection limit for silicate was 500 mg Si m^{-3}, with results reported as <500 mg Si m^{-3} presented as 250 mg Si m^{-3}.

Oyster growth, measured as milligrams of nitrogen gained per milligram N DTW per day, hovered between 0.002 and 0.004 (or put more simply, a 0.2–0.4% increase per day in tissue weight) over the two-year period, with no apparent seasonal pattern (Figure 14). On the other hand, the increase in oyster condition in each two-month period was reduced in the middle of summer each year, and the oysters actually lost condition in summer 2007–08 (Figure 14). The loss of condition in summer is likely to be a direct result of summer spawning. This appears to be broadly consistent with the annual reproductive cycle of *C. gigas* that has been widely described (e.g. Dinamani 1987; Ren et al. 2003). In temperate regions, *C. gigas* exhibits a seasonal reproductive cycle, clearly related to temperature with (1) initiation of gametogenesis usually observed in winter when water temperature is low; (2) an active phase of gametogenesis (growing stage) in spring when water temperature increased; (3) maturity and spawning in summer, when temperature was above 19°C (Mann 1979); (4) a resorption period in autumn (degenerating stage).

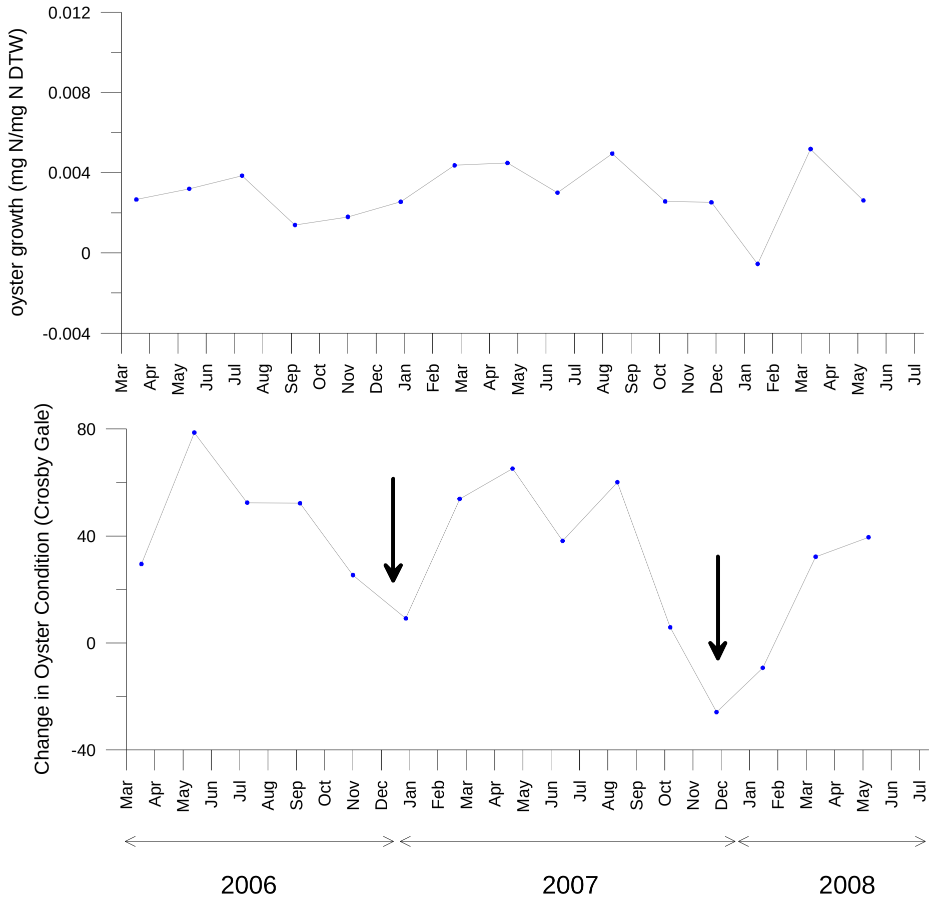


Figure 14 **Time series plots of oyster growth and the change in oyster condition (Crosby Gale 1990) measured in consecutive two-month deployments. Arrows represent likely time of spawning.**

Nitrogen budgets

Observation-based budget

Several key aspects of the nitrogen cycle in Little Swanport are apparent from the estuarine-wide annual average pools and fluxes of nitrogen, particularly when comparing the relatively wet 2004 with the very dry years of 2006 and 2007 (Figure 15). The estimated river load of dissolved inorganic nitrogen to the estuary varied between ~113 t in 2004 and 30 kg and 200 kg in 2006 and 2007 respectively. The corresponding load of detrital nitrogen was ~2.1 t in 2004 compared with 10 kg and 40 kg in 2006 and 2007 respectively. However, it is important to note that the accuracy of the annual load and flux estimates is directly related to the representiveness of the sample days used to calculate the budget. Webster et al. (2000) demonstrated the large errors that can occur if the sampling regime doesn't represent the time variant nature of the discharge loads. For this reason we suggest that the budget for 2004 is likely to be overestimated. In 2004, the January sample coincided exactly with the peak of a one-in-five-year flood.

With one sample day per month, the calculation essentially assumes that the conditions on that day prevail for the whole month, which is clearly not the case for floods of this magnitude. This is perhaps best described in terms of river flow; the 12 sample days used in the 2004 budget provide an estimate of 273 826 ML for the year compared with 28 295 ML when the January sample is excluded. The actual total river flow measured for the year was 31 250 ML. Nonetheless, there is still at least a five-fold greater load in 2004 compared with 2006 and 2007, with or without the January sample included (Figure 15).

The importance of oceanic exchange, and in particular, the influence of river flow on the magnitude of this oceanic exchange is also clearly evident. In 2004, there is a large export to the ocean because a significant fraction of the river input is washed directly out to the ocean during large river flows. In 2006 and 2007, oceanic exchange also led to a net export, albeit a much smaller one. The net export in all three years is largely a reflection of the higher annual average concentrations in the estuary compared to the ocean. Despite the increase in exports to the ocean when river flow is greatest in 2004, not all DIN constituents are flushed to the sea, and the standing stock of DIN, phytoplankton and detritus in the estuary are greater than 2006–07 as a result. The concomitant increase in oyster harvest was estimated at ~100 kg N which equates to a ~15% increase in 2004 relative to 2006 and 2007.

Phosphate and silicate were also routinely measured on these field trips, and annual budgets were calculated for these nutrients (Table 5). It must be emphasised that there was far less silicate data available for estimating river and ocean boundary conditions, so the silicate budget should be viewed with caution. In all three years the estuary was a net sink for phosphate, with more phosphate entering than leaving the system. Not surprisingly the net import was greatest in 2004 when river flow and oceanic exchange were greatest. For silicate, the budgets also indicated that the estuary was a net sink in all three years. The net flux of phosphate, ΔDIP, was also used to calculate net ecosystem metabolism and nitrogen fixation–denitrification following the LOICZ method described above. In all three years the system appears to be net autotrophic (2004 – 6.82 mmol C m^{-2} day^{-1}; 2006 – 5.13 mmol C m^{-2} day^{-1}; 2007 – 5.64 mmol C m^{-2} day^{-1}) and net nitrogen fixing ([1]2004 – 1.14 mmol N m^{-2} day^{-1}; 2006 – 0.41 mmol N m^{-2} day^{-1}; 2007 – 0.39 mmol N m^{-2} day^{-1}). For these stoichiometric-based estimates it must be kept in mind that the calculations assume that absorption and burial of DIP is negligible in coastal waters, but evidence from other systems such as Port Phillip Bay suggests we should be cautious about ignoring it. Nonetheless, direct estimates of ecosystem metabolism in the water column and over-vegetated and un-vegetated benthic habitats throughout the Little Swanport estuary (NAP TEFlows, *unpub data*) in spring and autumn 2007 and 2008 also demonstrate net autotrophy for the system. Unfortunately, there have been no direct estimates of denitrification or nitrogen fixation in the estuary to support or refute the LOICZ stoichiometric estimates. Although nitrogen fixation is ordinarily slow or absent in marine systems (see

[1] The sample collected during the January 2004 flood was excluded from this calculation.

Carpone 1988), high rates have been reported in seagrass communities (Hansen et al. 2000), and thus it is plausible that Little Swanport is slightly net nitrogen fixing.

The 2004 budget calculations highlight that the system is not necessarily well characterised as being a steady-state system, but that temporal variation is an important characteristic. To demonstrate this, the individual spot measurements used to calculate the annual budgets are shown in Figure 16 and Figure 17. It is evident that that the oceanic exchange switched between net export and net import (Figure 16C), depending on the relative concentrations in the estuary and ocean (Figure 16B). The two sample dates highlighted in Figure 16 also demonstrate that the magnitude of the oceanic exchange is proportional to the difference between the oceanic and estuarine concentrations. Similarly, the stoichiometric estimates of net ecosystem metabolism and nitrogen fixation-denitrification indicate significant temporal variation, with the system becoming net heterotrophic and denitrifying in late spring – early summer and net autotrophic and nitrogen fixing in between.

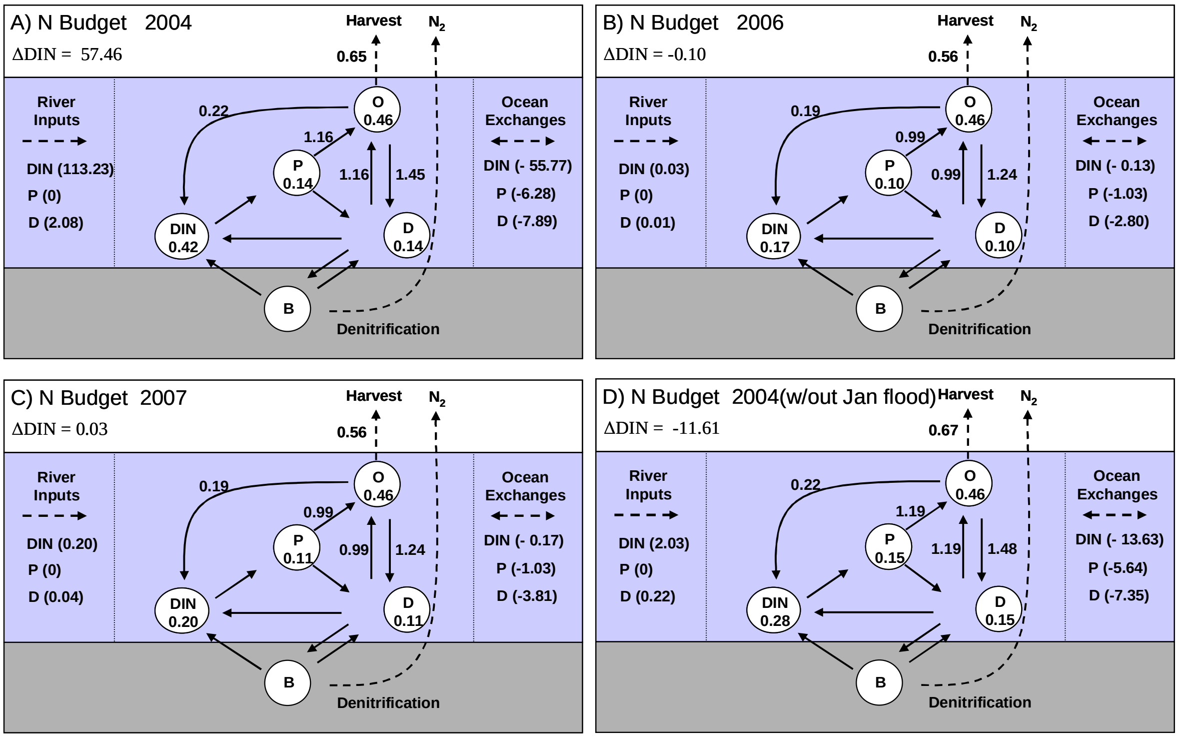


Figure 15 **Annual observation-**based nitrogen budget (pools and fluxes) in Little Swanport calculated for (A) 2004, (B) 2006 and (C) 2007 when the total river flow into the estuary was 31 251, 1238 and 4258 ML respectively. (D) represents the 2004 budget when the sample corresponding to a major flood in 2004 was excluded. Solid arrows represent internal fluxes, and dashed arrows are external inputs and outputs. State variables are annual averages (t N) and all other quantities are annual fluxes (t N year^{-1}).

Table 5 Annual phosphate and silicate budgets.

Phosphate budget (tonnes)				
	River load	Ocean exchange	Net	Standing stock
2004	0.16	0.56	0.72	12.63
2006	0.01	0.45	0.45	10.86
2007	0.02	0.38	0.40	13.12
Silicate budget (tonnes)				
2004	3572.00	-2745.00	826.00	6728.00
2006	13.05	5.72	18.77	925.52
2007	56.46	-6.56	49.90	976.69

Ecosystem model-based budget

To gain insight into the other major pools and fluxes which could not be directly estimated in an observation-based nitrogen budget, the annual pools and fluxes estimated by the ecosystem model were compared (Figure 15 and Figure 18). In general, the model reproduces similar pools and fluxes to the observation-based budget. The major difference was the higher estimates for the oyster harvest and biomass of detritus in the water column in the observation-based budget. However, it is important to note that there were few instances when phytoplankton biomass and detrital biomass were measured concurrently, and thus, the 50:50 split assumed in the observational budget should be treated with caution. Irrespective of the budget method used, oyster harvest, DIN, P and D pools were higher in the wet years of 2004 and 2005 compared to dry years of 2006 and 2007. With the exception of seagrass production, rates of primary (phytoplankton and microphytobenthos) and secondary production (zooplankton and oysters) were also higher in wet compared to dry years.

There were a number of other key aspects of the nitrogen cycle in Little Swanport apparent from the model. The flux of nitrogen through the primary producers, seagrass, phytoplankton and microphytobenthos, far outweighs the external loads due to the efficient internal recycling in the sediments and water column. Although the phytoplankton pool is very small compared to seagrass and microphytobenthos, phytoplankton production is very high due to its rapid turnover rate. In contrast, the seagrass and microphytobenthos pools are much larger, but turn over much more slowly. Secondary production in the form of zooplankton growth also represents a major flux of nitrogen despite the small zooplankton pool. In contrast, the flux of nitrogen through oysters is comparably small, despite representing a larger pool of nitrogen in the water column than phytoplankton and zooplankton.

Of the phytoplankton primary production, ~46 % sinks to the sediment, ~42% is consumed by zooplankton, ~3% is consumed by oysters and ~10% is exported to the ocean. Although phytoplankton primary productivity was higher in the wet compared to the dry years, a greater proportion of the primary productivity generated in the dry years was recycled internally. For example, in the dry years of 2006 and 2007, there was a 2–3% increase in the proportion of the phytoplankton productivity recycled internally via zooplankton grazing and sedimentation. This is because the average flushing time is longer (and hence the chance of being exported to the ocean is reduced) in the dry (~11 days) compared to the wet years (~8 days). In the wet years ~12% of phytoplankton productivity is exported to the ocean compared with ~7% in the dry years. The dominant form of nitrogen in the river inputs and water column in the estuary is dissolved organic nitrogen (DON). Not surprisingly, DON also accounts for most of the nitrogen fluxing across the ocean boundary. In wet years of 2004 and 2005 when estuarine concentrations are high and flushing times are reduced, a large proportion of the river load is exported to the ocean, but in the dry years of 2006 and 2007 when estuarine concentrations are reduced, there is a net import of DON from the ocean. Of the organic nitrogen deposited from the water column that is fluxed through the sediments, denitrification removes ~40%.

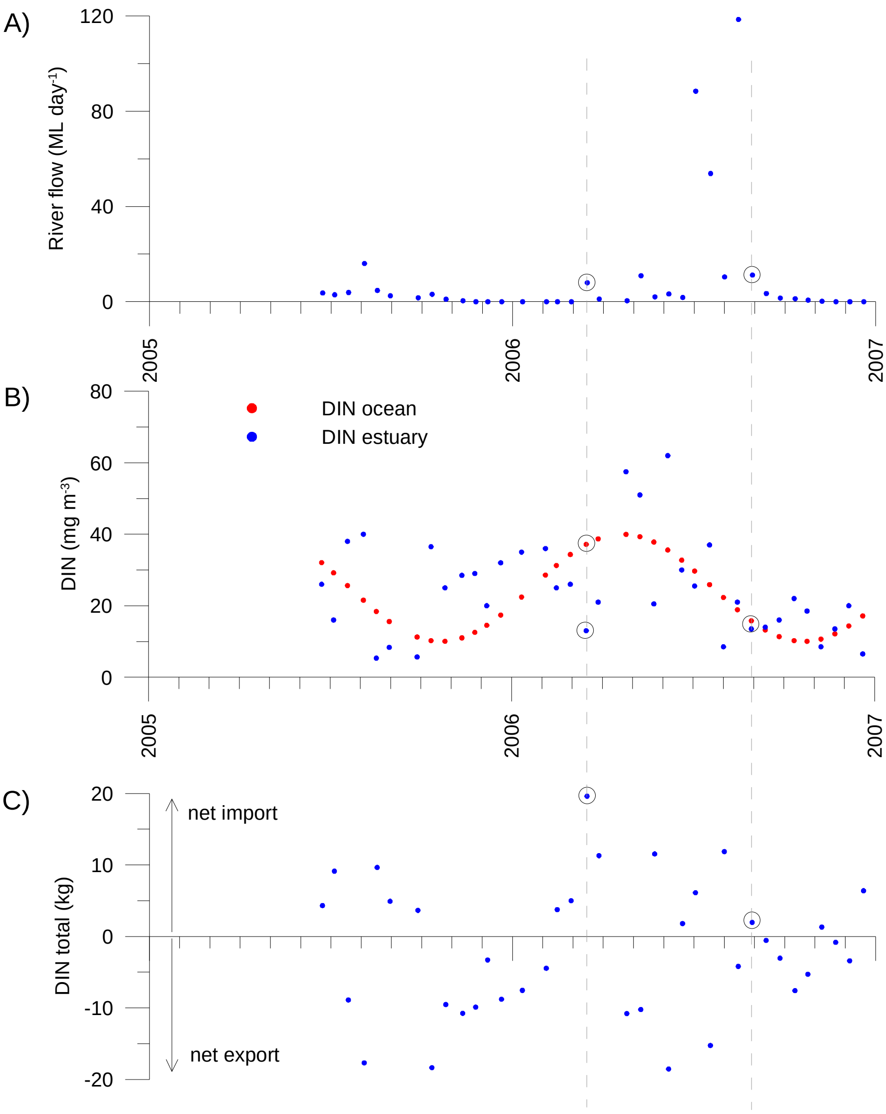


Figure 16 Temporal variability in river flow (A), estuarine and oceanic DIN concentrations (B), and net import to and net output from the Little Swanport estuary (C). The dashed lines and circled data points identify the two sample dates discussed in the text.

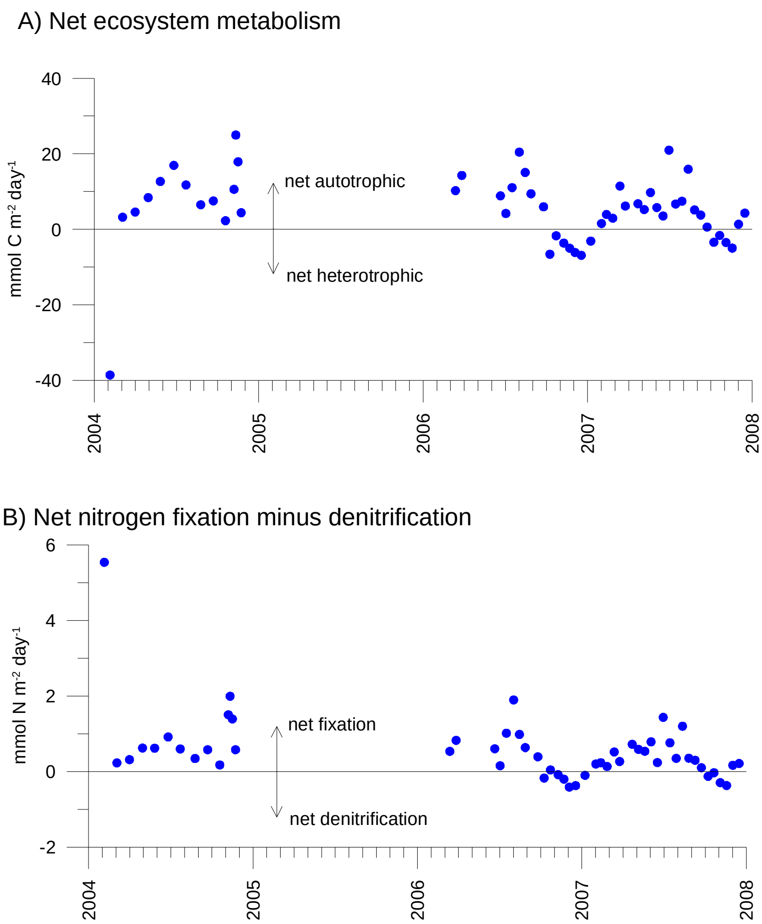


Figure 17 Temporal variability in (A) net ecosystem metabolism and (B) net nitrogen fixation-denitrification.

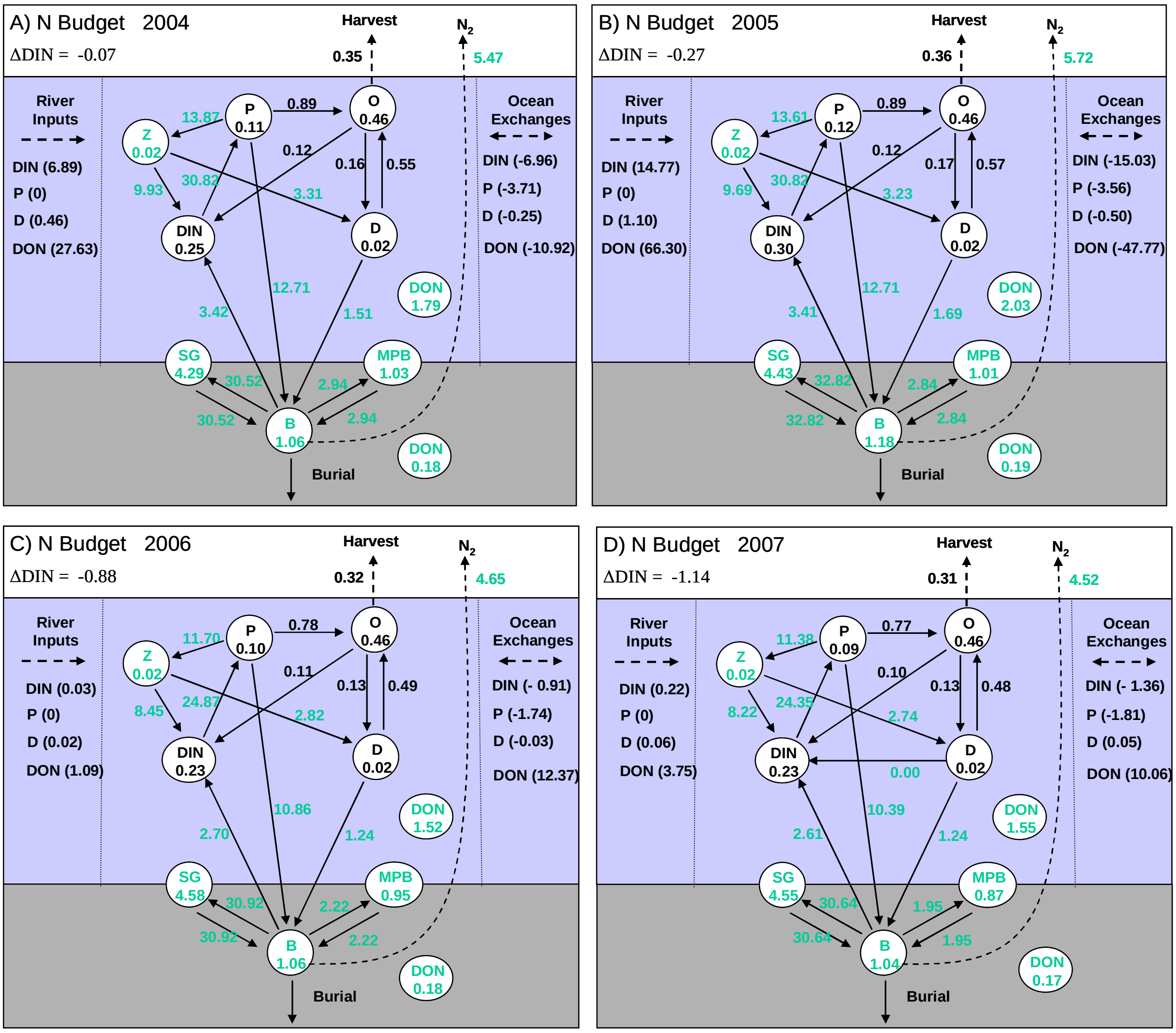


Figure 18 Annual model-based nitrogen budget (pools and fluxes) in Little Swanport calculated for (A) 2004, (B) 2005, (C) 2006 and (D) 2007 when the total river flow into the estuary was 31 251, 75 258, 1238 and 4258 ML respectively. Solid arrows represent internal fluxes and dashed arrows are external inputs and outputs. State variables are annual averages (t N) and all other quantities are annual fluxes (t N year^{-1}).

Ecosystem box model

Effects of base river flow on estuarine dynamics

A major goal of the study was to understand the importance of river flow to the functioning of the estuarine ecosystem. To gain a general understanding of the role of base river flow to the estuary, model simulations were carried out for a two-year period, and the outputs compared across simulations with different base flows, ranging from 0 to 200 ML day^{-1} (Figure 19). Over this range, there is a non-linear increase in the average phytoplankton biomass with increasing base flow. Phytoplankton biomass increases rapidly with base flow from 0–20 ML per day, before the rate of increase slows to a more steady rate as base flow increases over 40 ML per day (Figure 19a). Not surprisingly, given that oysters feed on phytoplankton, oyster growth shows a similar response to increasing base flow (Figure 19b). These non-linear responses are driven largely from the non-linear relationship between flushing time and river flow that was determined when developing the transport model (Figure 8): as river flow increases, flushing time decreases rapidly, but at high river flows flushing time is relatively stable. At low river flows, phytoplankton have more time to take up the additional nutrient inputs from the river because the flushing times with the ocean are long. As river flow increases, this uptake obviously drops off as flushing time shortens. In other words, the greatest benefits per megalitre of river flow for phytoplankton production and oyster growth are at low base flows; increasing base flow from 1– 40 ML per day leads to an ~11% increase in oyster growth rates and it isn't until the base flow reaches 200 ML that another ~11% increase in growth is reached.

In contrast to phytoplankton biomass and oyster growth, zooplankton decreases with increasing base flow (Figure 19c). This is largely because zooplankton has a slower turnover rate and any increase in biomass is countered by increased export to the ocean as a result of the increase in flushing time with river flow. Although oysters have even slower turnover rates, they are not subject to being flushed from the estuary. Similarly, microphytobenthos which live for the most part on the sediment surface are not likely to be susceptible to being flushed from the estuary at this range of base flows, explaining why their biomass also increases with base flow, particularly at low flows (Figure 19d).

Interestingly, seagrass, the other major benthic primary producer, also increases in abundance at low flows, but declines in abundance once the base flow reaches ~60 ML per day (Figure 19e). This is because seagrass is susceptible to overgrowth by epiphytes when nutrient concentrations are high (e.g. Madden & Kemp 1996). Although epiphytes are not modelled explicitly, they are represented as an additional specific loss rate for seagrass that is proportional to DIN concentrations in the water column, which increase in concentration with base flow (Figure 19f).

At this point it is important to note the role that the river flow versus river DIN concentration relationship plays in modulating the above response. Unlike the other constituents that are delivered in river water, the DIN concentration didn't appear invariant to river flow, and in fact increased with river flow in a non-linear fashion as modelled in Figure 5. In order to demonstrate the effect of this relationship the base flow scenarios were re-run with a constant river DIN concentration of 26 mg N m^{-3} (Figure 20). Although the responses were similar at low flows, as one might expect, the effects were greatest at high flows when the change in river DIN and subsequent DIN loads were greatest. The benefits of increasing base flow at high flows for phytoplankton and oyster growth were reduced when river DIN was constant, and the decline in seagrass at high flows was also reduced. This again appears to be directly related to the estuary DIN concentrations and the subsequent epiphyte response.

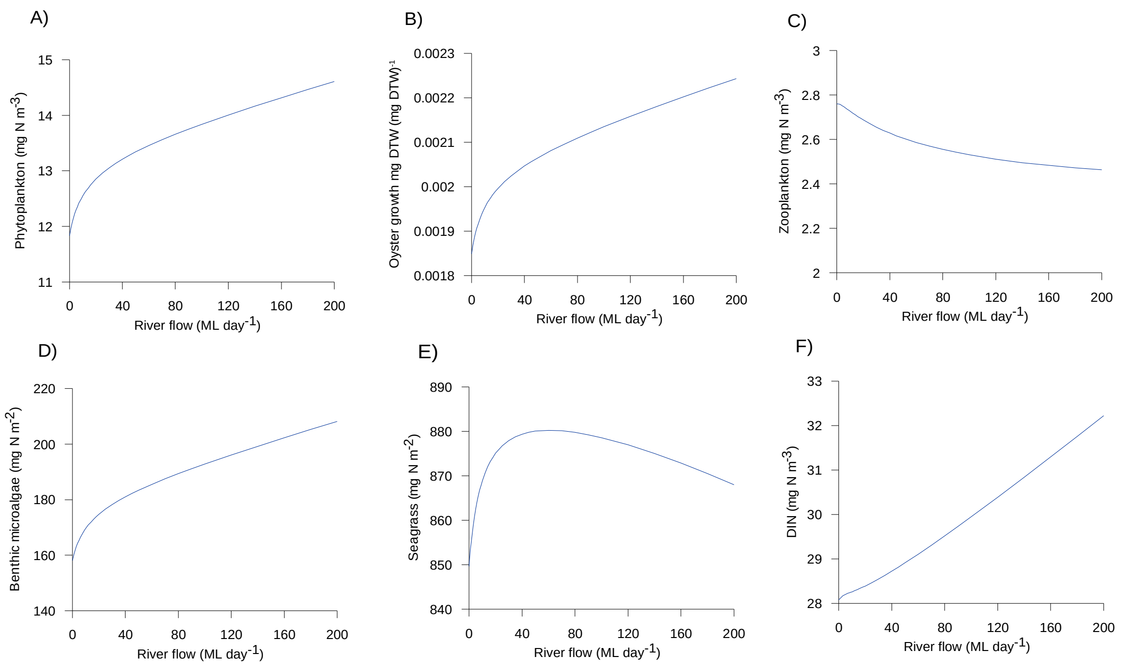


Figure 19 Effects of base river flow to the estuary. Base flow was kept constant for a two-year period, and the average outputs compared across simulations with different base flows, ranging from 0 to 200 ML day^{-1}.

Given the seasonal patterns observed for many of the state variables in the model simulations, it seems likely that the fluxes into and out of the estuary that underpin the net response discussed above are also going to vary temporally. This is highlighted for phytoplankton and DIN in Figure 21. For both DIN and phytoplankton, it is clear that the magnitude of the flux depends on the river flow (and hence flushing time) and the size of the difference between the ocean and estuarine concentrations, and the direction of the flux depends on whether the ocean or the estuary has the highest concentration. From January to June, DIN concentrations are lower in the estuary than the ocean and there is a net import of DIN into the estuary from the ocean, but for the remainder of the year the concentration is higher in the estuary and there is a net export of DIN from the estuary. The magnitude of these fluxes is greater when base river flow is 100 ML per day compared to 10 ML per day because the flushing time is shorter, and hence, the volume of water exchanged with the ocean is greater. In the case of phytoplankton, the estuary is a net exporter to the ocean. However, the magnitude of this exchange is at its greatest in late summer and lowest in winter, with the difference exacerbated during high flows compared to low flows.

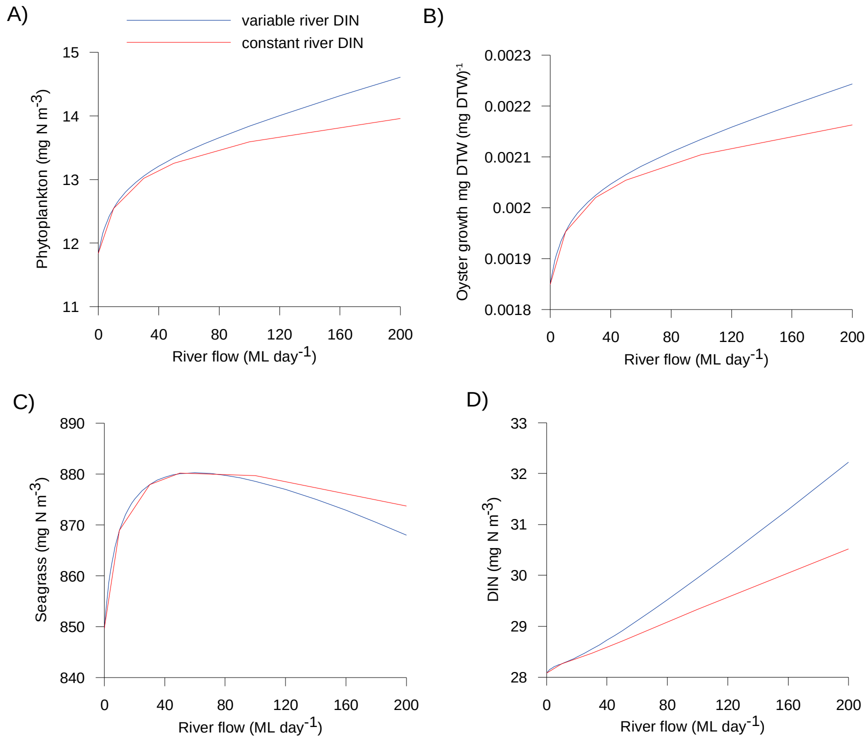
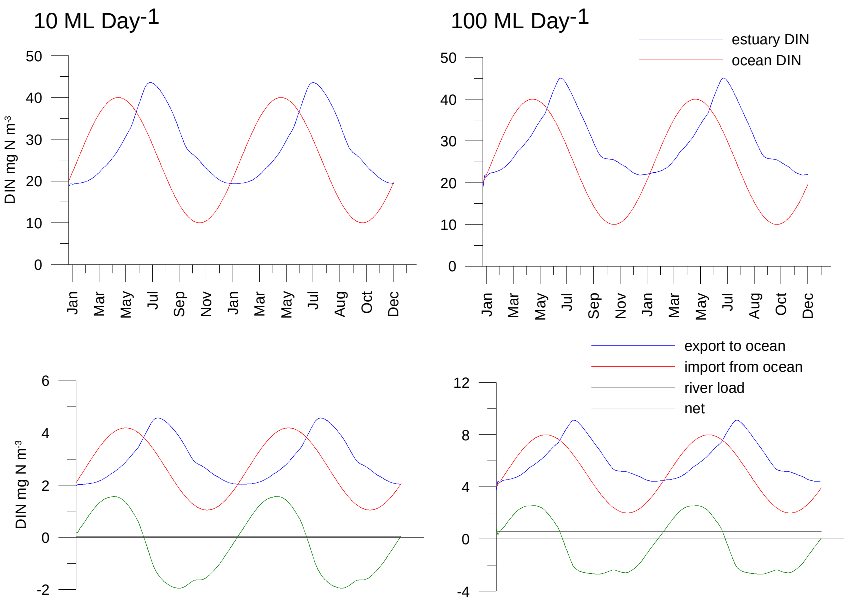


Figure 20 Comparison of the effects of base river flow on A) phytoplankton, B) oyster growth, C) seagrass and D) DIN, with constant versus variable river DIN concentration.

These results also suggest the simple hypothesis that the greatest benefits of river flow to phytoplankton production will come from flows in winter months when the difference in ocean and estuarine concentrations, and hence loss to the ocean, is at its minimum. As it stands, the Water Management Plan for the Little Swanport catchment has cease-to-take periods that allow for greater environmental flows in winter than in summer (≤7.6 ML per day, November to April, and ≤9.5 ML per day, May to October). Ostensibly based on the environmental water requirements of the Little Swanport River rather than the estuary, our simple hypothesis for the estuary suggests that this will also have maximum benefit for estuarine productivity. To test this hypothesis explicitly, the model was re-run using targeted seasonal flows, comparing the estuarine response when all river flow was in winter (100 ML per day from June to October) versus when all river flow was in summer (100 ML per day from November to March). Interestingly, the reverse was actually true (Figure 22), with greatest productivity achieved following summer rather than winter river flows. This is because although losses to the ocean were reduced with winter rather than summer flows, growth rates of phytoplankton are limited by temperature in winter and there was virtually no detectable increase in biomass. In contrast, during the summer flows, increases in production in the estuary far outweighed the increase in losses to the ocean.

A) Disolved Inorganic Nitrogen



B) Phytoplankton

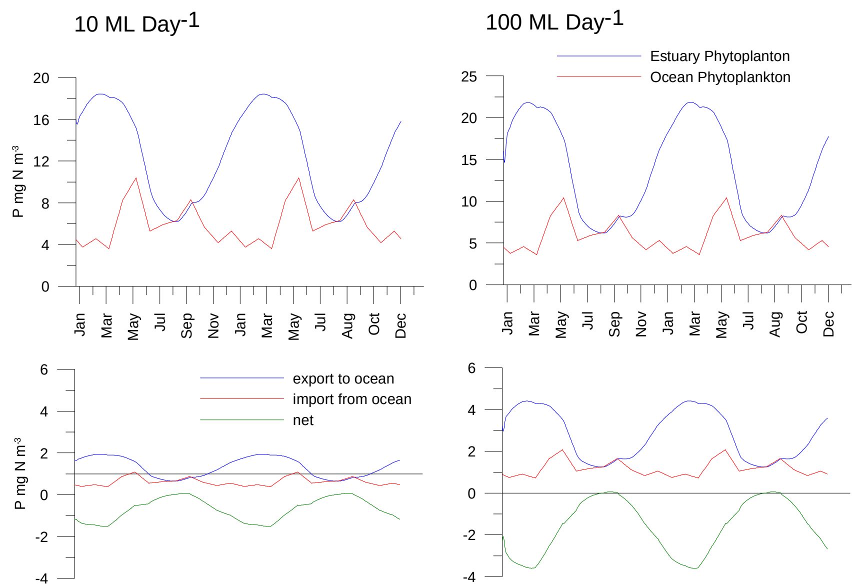


Figure 21 **Comparison of river and ocean inputs and exports of A) DIN and B) phytoplankton for base flows of 10 and 100 ML day-1.**

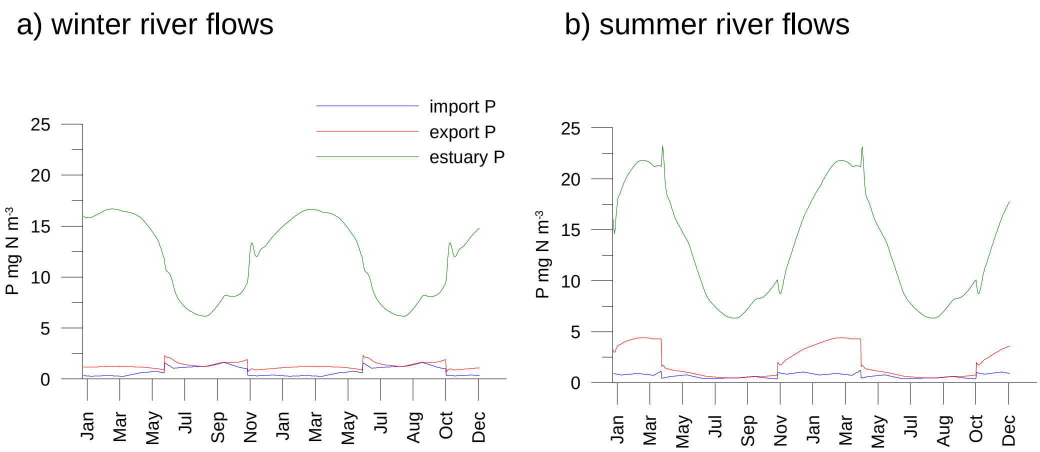


Figure 22 Comparison of the phytoplankton response, including the biomass imported from and exported to the ocean, with a) winter river flows (100 ML day^{-1} from June to October), and b) summer river flows (100 ML day^{-1} from November to March). Note: river flow was set to zero outside the respective flow periods.

Effects of the drought on estuarine dynamics

One of the most powerful tests of the importance of freshwater flows to an estuary would be to compare years at each end of the potential extremes; times characterised by high flows compared with periods characterised by very low or no flows. If differences in the health and productivity of the estuary are not evident between these extremes then it would seem unlikely that more subtle changes are likely to be significant. Therefore, a comparison of model outputs for the two drought years of 2006 and 2007 (when the total flow into the estuary was 1238 and 4258 ML respectively) with the two years prior to this, 2004 and 2005 (when the total flow into the estuary was ~31251 and 75258 ML respectively), provided a critical test of the importance of freshwater flows to the Little Swanport estuary. Model outputs for some of the key state variables and important fluxes are shown in Figure 23. It is clear that the major river flow events in 2004 and 2005 led to an increase in DIN concentrations in the estuary and subsequent phytoplankton blooms in the estuary. The increase in phytoplankton biomass also led to an increase in zooplankton biomass, albeit of a smaller magnitude. As we discovered in the base flow comparison above, the higher estuarine DIN concentrations following the floods led to a decline in seagrass biomass due to epiphyte growth on seagrass fronds. There was also a response by benthic microalgae to the floods (Figure 23); however, this was far more subtle than that of the other primary producers, particularly phytoplankton. This is likely to reflect a combination of the slow turnover rates and dependence on DIN in the sediments by benthic microalgae.

As we might expect, the increased production of organic matter following the floods led to a concomitant increase in the supply of organic matter to the sediments as evidenced by the response in rates of sediment denitrification and release of DIN back into the water column.

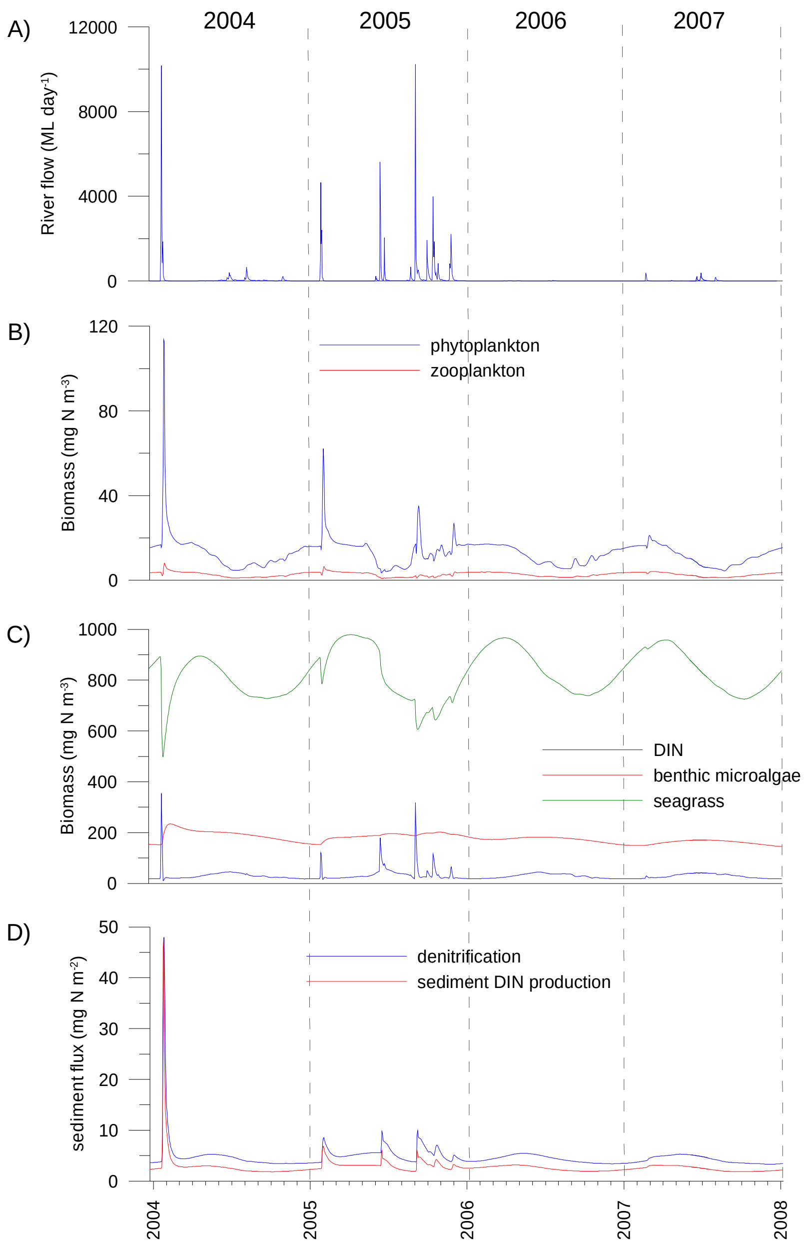


Figure 23 Time series plot of (A) river flow into the estuary and the model responses for (B) phytoplankton and zooplankton biomass, (C) dissolved inorganic nitrogen concentration in the water column, benthic microalgae and seagrass biomass, and (D) rates of sediment denitrification and dissolved inorganic nitrogen release from the sediments.

In gross terms, when the responses shown in Figure 23 are integrated over the respective two-year periods, the model predicts (Table 6) that the 95% reduction in river flows from 2004–05 to 2006–07 led to a 15% reduction in estuarine DIN concentrations and phytoplankton biomass, an 11% reduction in benthic microalgae biomass, a 12% reduction in oyster harvest, a 1% reduction in zooplankton biomass and a 5% increase in seagrass biomass.

Table 6 Comparison of total oyster harvest, average biomass of phytoplankton, seagrass, MPB and zooplankton, and the average concentration of DIN in the estuary from 2004 to 2007.

Year	River flow (ML)	Oyster harvest (kg)	Phytoplankton (kg)	DIN (kg)	Zooplankton (kg)	MPB (kg)	Seagrass (kg)
2004	31361	350.9	109.6	251.9	22.0	1034.2	4288.1
2005	75258	362.2	116.1	295.0	22.3	1009.5	4433.3
2006	1238	316.1	97.4	232.9	22.1	948.0	4582.1
2007	4258	310.5	94.9	231.9	21.5	870.2	4549.1
change (04-05 vs. 06-07)	50562	43.3	16.7	41.1	0.3	112.7	-204.9
change as % of 04-05	-95%	-12%	-15%	-15%	-1%	-11%	5%

Effects of WMP (2006) increased allocation on estuarine dynamics

As part of the Little Swanport Water Management Plan (2006) the catchment allocation limit (the total amount of the catchment's water resource that can be allocated for stock and domestic or irrigation purposes) was increased from 3882 Ml per year, which was the allocation for agriculture set during the development of the plan, to 6084 ML per year. To assess the impact of the increased allocation on the estuary, the model simulations using hydrographs of the flow regime under the previous allocation limit were compared with model simulations using hydrographs under the plan. This was repeated in a dry year and in an average year (Figure 24). The model outputs for both allocation scenarios were barely distinguishable, as evidenced for phytoplankton and oyster growth in an average year and a dry year in Figure 25. This is further illustrated in Table 7 (a dry year) and

Table 8 (an average year) which compare the total oyster harvest, the average biomass of phytoplankton, seagrass, and zooplankton, and the average concentration of DIN in the estuary under the different allocations.

The average dry year represents a flow of ~20 000 ML per year, yet only 1238 and 4258 ML per year were estimated for 2006 and 2007 respectively. In these circumstances (i.e. drought years), full allocation is likely to have different consequences for the estuary than determined for the average and dry years above. For this reason, we ran the model for a 'very dry' year (2007) assuming the actual flow represents the current allocation. The full allocation hydrograph was created by allocating water across the year within the cease to flow and flood harvesting requirements (Figure 25). In contrast to previous cases, there was a discernable difference between the current and full allocation scenarios in the very dry year scenario. The model predicted that the reduced load of nutrients to the estuary in the February flow event, due to likely water harvesting under the full uptake conditions, would lead to a decline in estuarine nutrient concentrations and a subsequent repression of the phytoplankton and oyster growth responses. However, in winter, when estuarine nutrient concentrations are already higher and growth rates are limited by temperature, the model predicts that harvesting flows of a similar magnitude will have a negligible effect on phytoplankton and oyster growth. Taken across the whole year, the changes due to full allocation are relatively small. Changes of this magnitude fall within the uncertainty inherent in model simulations and, as such, should be treated with caution. The important message is that harvesting water during a very dry year is more likely to have an effect on the estuary, particularly in summer months.

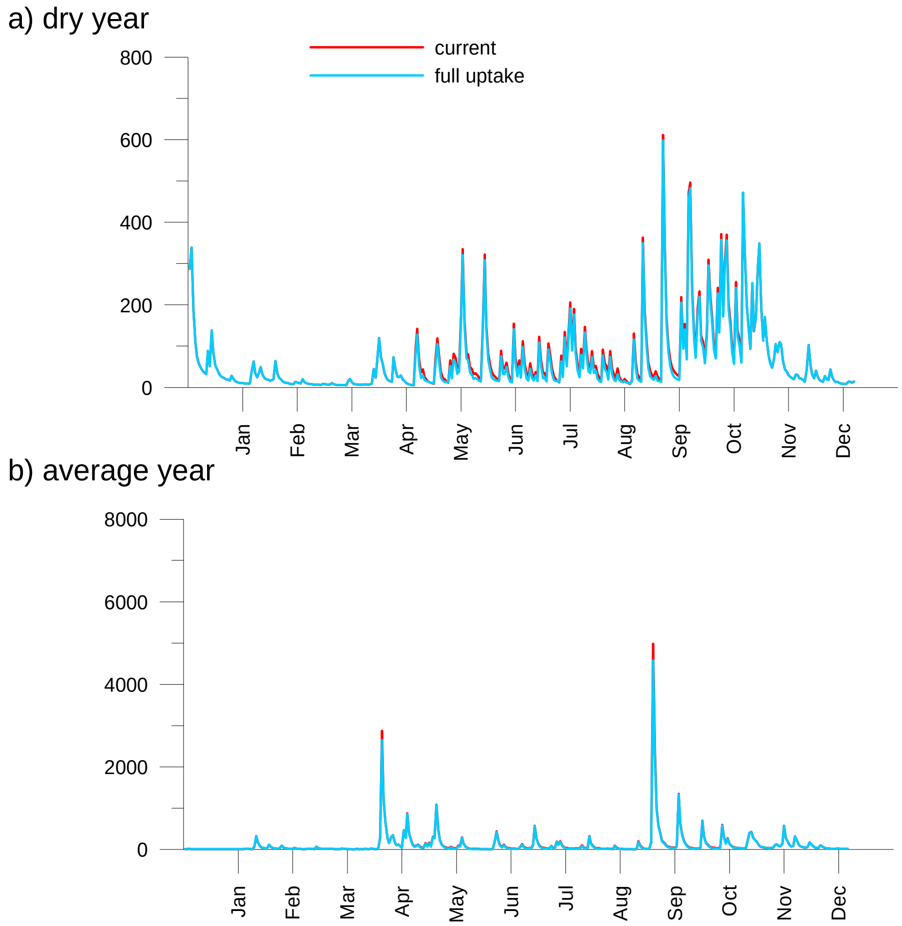


Figure 24 Flow regime (ML day^{-1}) at the Little Swanport River outlet under natural, current and full uptake (under the Plan) conditions in (a) a dry year and (b) an average year.

Table 7 Total oyster harvest, average biomass of phytoplankton, seagrass, and zooplankton, and the average concentration of DIN in the estuary under current and full uptake (under the plan) conditions in a dry year.

	current	full	change	%
Oyster harvest (kg)	343.480	343.159	0.321	0.000002
Phytoplankton (kg)	106.718	106.611	0.107	0.000015
Seagrass	7156.356	7158.753	-2.397	0.000017
DIN (kg)	236.128	235.513	0.615	-0.000027
Zooplankton (kg)	21.083	21.171	-0.087	-0.000033

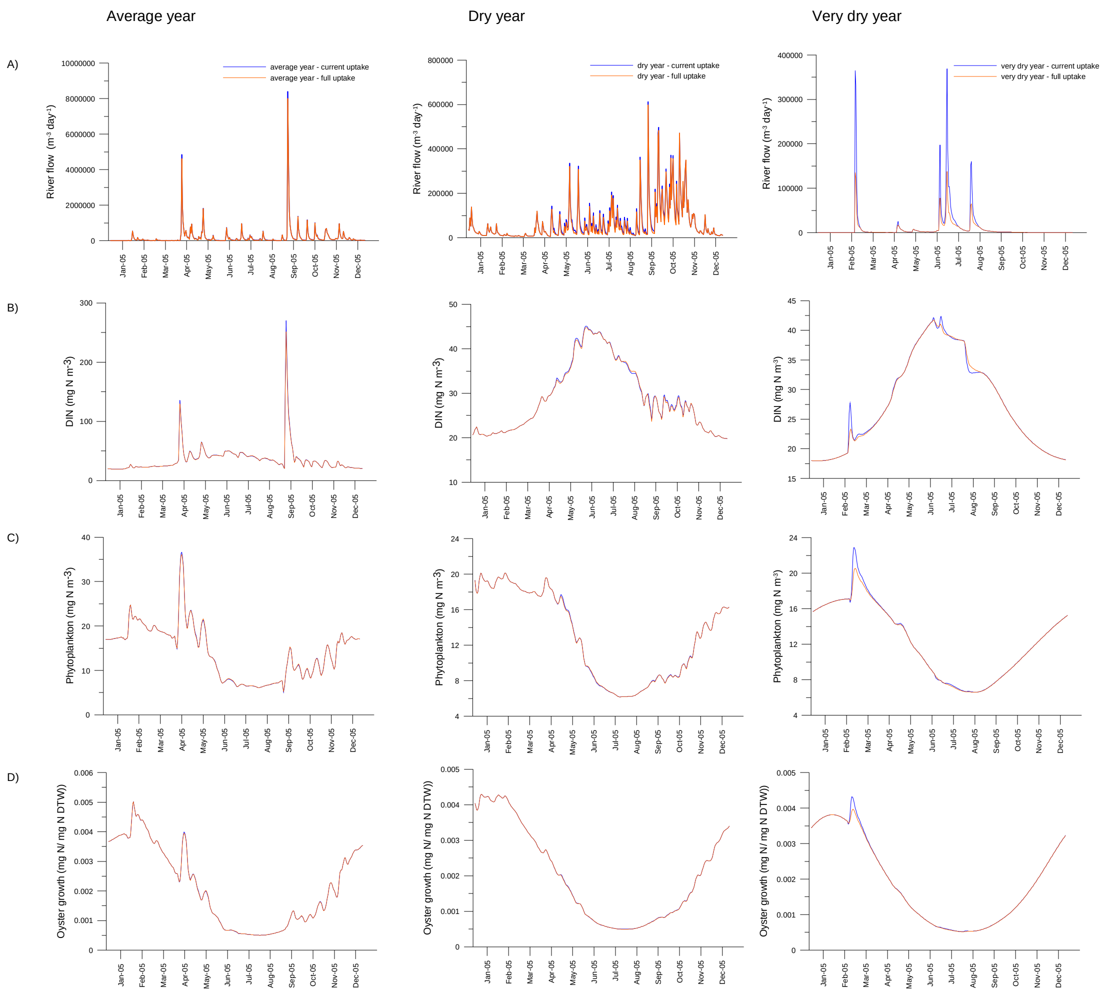


Figure 25 Responses of b) DIN, c) phytoplankton and d) oyster growth to the flow regime ($m^3\ day^{-1}$) at the Little Swanport River outlet under current and full uptake (under the Plan) conditions in an average year, a dry year and a very dry year (2007).

Table 8 Total oyster harvest, average biomass of phytoplankton, seagrass, and zooplankton, and the average concentration of DIN in the estuary under current and full uptake (under the plan) conditions in an average year.

	current	full	change	%
Oyster harvest (kg)	361.585	361.503	0.081	0.000002
Phytoplankton (kg)	115.589	115.600	-0.011	0.000015
Seagrass	6630.757	6668.850	-38.092	0.000017
DIN (kg)	288.656	286.294	2.363	-0.000027
Zooplankton (kg)	20.828	20.896	-0.068	-0.000033

Table 9 Total oyster harvest, average biomass of phytoplankton, seagrass, and zooplankton, and the average concentration of DIN in the estuary under current and full uptake (under the plan) conditions in an average year.

	Oyster (kg N)	Phytoplankton(kg N)	DIN (kg N)	Zooplankton (kg N)
2007 - current	325.1	101.1	223.5	22.5
2007 - full uptake	320.8	100.3	223.0	22.6
change current to full uptake	1.31%	0.73%	0.20%	-0.18%

Objective 2 The value of water in a drying climate

Introduction: Accounting for water

No natural resource is "an island" and water is perhaps the most interdependent resource of all. All natural resources are intimately connected to others by complex and powerful ecological and other biophysical processes. For example, the forests that depend upon the sun, water, and soil also have marked effects on the conditions and services provided by water and soils. With the profound rise in the influence and impact of human (or "anthropogenic") activity on natural cycles, society (and its economy) are now central components of the water cycle and the related web of natural resource interactions.

Water is not just a precondition for economic prosperity but is critical for the integrity of life itself. Australia has long been the driest continent on Earth (excluding the unusual context of Antarctica).

When we combine the fundamental necessity for water with the need to understand resources as part of closely interconnected natural systems, there is little wonder that *integrated water resource management* has become a major focus and approach of modern environmental management and science.

Integrated water resource management is:

a process, which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

(Global Water Partnership Technical Advisory Committee 2000 p22).

The benefits of focusing analysis and planning within the hive of resource interconnections of bio-geographic regions are now widely appreciated. They are actively pursued in the broader notion of *integrated catchment management.* Once resource flows and use were studied in a piecemeal fashion in *ad hoc* regions – often geopolitical in nature. In the new bioregional and integrated approach, the catchment as a water flow network system provides the basis for capturing and understanding all major ecosystem elements as well as related human, economic and social activities, impacts and values. The integrated catchment approach fits neatly with land and water management decision-making processes that link closely to local stakeholders who are directly involved in the services provided by this natural area.

Catchments as the basis for the integrated measurement and management of natural resources

The geography of water can be a primary basis for the management of all natural resources in a region. The catchment is the appropriate unit for understanding and planning natural resource use in a way consistent with natural regeneration processes and cycles. The ability to work with the key processes of a catchment enhances the ability to (non-destructively) utilise nature's flows of materials and energy (for example, gravity-fed freshwater supplies), and to minimize material and energy disruption in providing services to humans.

This central role of water in the integrated study and management of natural resources reflects the remarkable importance of the substance. Water underpins and connects all forms of life. The strength of this connection means that identifying, understanding and measuring the main stocks, flows and processes associated with water is vital for effective human-environment interaction. Understanding and measuring tend to be close partners in decision-making based on science.

In the past, the study of water as an environmental resource was dominated by hydrology, a related natural science discipline. This emphasis followed on from an assumption that the water cycle is largely unaffected by, and operates primarily outside of, the human domain. This, of course has not been true for a very long time in settled communities, as we have already discussed. Today, the scale of interaction between human activity and the "natural" water cycle is so significant that it is not possible to effectively study water just as a hydrological phenomenon directed by natural systems. The linkages between the water cycle, other natural fluxes and resource conditions, and human activities, are pervasive. They include interconnected aspects such as the extent and type of vegetation and land uses, water abstractions and translocation, energy production and use; and these have links to microclimate, rainfall levels and variability, temperature, evapotranspiration, runoff and surface and groundwater flows. The land cover and water stocks and flows of most catchments are significantly affected by human activities.

As a result of these numerous interconnections, it is inappropriate, and ultimately misleading, to only consider isolated parts of catchments which may remain in near-natural state. Water provides an exemplary case of the vital role of resource flow linkages between society and nature. It is perhaps the only resource that largely retains its essence (given quality changes) as it provides four major functions to humanity : (1) in ecosystem services within nature (for example, the role of moisture in creating productive soil conditions) (2) as an economic input (3) as a consumption product in itself, and (4) as a residual or waste product or loss removed from the economic system back to nature (United Nations 2003). When we note that the primary aim of studying water cycles is to provide sustained welfare flows to society, it becomes clear that an intrinsic part of this endeavour is to understand and measure the links between water in nature and its use by, and impact upon, society. An integration of the natural and social sciences comprises an ideal laboratory for interdisciplinary approaches that are necessary to effectively manage water on a sustainable basis (in terms of all three criteria – economic, social and ecological).

Hence, a major prerequisite for water management is to identify and quantify the stocks and flows of water for both natural and human components, with the catchment as the system boundary. This pre-empts the need to move beyond the specialised and partial approaches of hydrological modelling that have prevailed in the past, towards the development of much more comprehensive empirical water accounts which "map" the significant stocks and flows within and between both nature and society. Such comprehensive water accounting inevitably creates the framework that sets out the path for the integration of biophysical and socio-economic dimensions of water within a catchment.

Water accounting and budgets

Water accounting is a general term for the systematic collection and compilation of empirical information measuring physical volumes of water flows and water stocks within a defined system boundary (such as a catchment). Accounting exercises, be they biophysical or monetary, tend to implicate the principle of balance. With a given system boundary, flows into the system must equal flows out of the system and any difference must be attributed to change in the stock within the system. This principle has more subjective potential for monetary accounts but, for most biophysical phenomena, mass balances must exist for predefined systems in accordance with the first law of thermodynamics (Ayres 1978).

The idea of balancing accounts for water supply, use and stock levels provides the cradle for the notion of *water budgets*. In a general sense, water budgets are a summary technique for balancing inputs and outputs through a system such as a nation, water management area, catchment, stream or groundwater reservoir. The impetus for budgets invariably involves the careful accounting of water in order to use it prudently. As with a household's budget, it involves knowing what "income" (water supplies) one has access to, and how that income is "spent" (water use) and whether this pattern of "expenditure" is what we want, or is giving us the best outcome. Water accounts provide the necessary data for the budgeting process to assess the desirability of different uses of limited resources.

"The water budget at a place is an appraisal of inputs and outputs in the same way we would describe our financial affairs" (Leaman, 2007 p7). While this is certainly true, there are some significant differences. Most of us expect a constant pay-packet, week-in, week-out. The exceptions to this are (mainly) small business people who, more so than anyone else, are subject to the vagaries of the market. Rainfall can be as irregular as the income of small business. Farmers are the classic case where both natural and economic dynamics combine to lead to great uncertainty. The "income" of our water budget is rain. We will see later just how variable that can be in our case study catchment.

With water budgeting, the aim is to ensure that reductions or limitations in inputs are addressed by allocating these inputs to those uses or outputs considered essential or giving the highest returns to the decision-making unit under study (for example, the household, organisation or broader community). Budgeting is intimately tied to the concept of "efficiency' and is a central (if often implicit) concept in economics. The conversion of physical quantities such as volume, to dollar values, is often a key part of this analysis of welfare (net benefits or value), derived from a resource.

Under the principles of sustainable development, our use of water has to meet specific criteria. Amongst other things this requires us to measure the benefits and/or costs of a large range of feasible "interventions" in the water cycle. To date, the only discipline which has a rigorous – but nevertheless problematic – method of measuring water in its various uses or demands is economics. Hydrology and related natural science disciplines have a supply-side emphasis on water processes. When economics and natural sciences are combined, we have the platform for a powerful new framework of water accounting.

Our goals for water accounting in Little Swanport

A major aim of our water accounting efforts are to make progress towards the systematic compilation of reliable and comprehensive information about the water cycle of a predominantly rural catchment – in our case, Little Swanport in Tasmania, Australia. The Little Swanport Catchment has been subject to several, quite detailed, studies of its hydrological characteristics. The most relevant existing studies include the hydrological focus in reports by the DPIWE (2003; 2007b) and a water balance assessment of the catchment covering both (1) natural supply-oriented climate and hydrological aspects, as well as (2) socioeconomic and institutional dimensions such as water entitlement, use, and farm dam water use and flow impacts under a variety of policy or regulatory scenarios (Sinclair Knight Merz 2004). There are also a number of other useful reports containing water-related and detailed land use and socioeconomic data utilised in the preparation and review of the Little Swanport Catchment Water Management Plan (for example, (Little Swanport Catchment Committee 2002; Resource Planning and Development Commission 2006).

While it is a relatively minor catchment in terms of overall national geographic and economic significance, this interest has been galvanized as a result of the perceived significance of human impacts upon the natural water cycle and serious competition for water use by different user groups in the catchment (mainly pastoral and aquaculture activities).

The models we have developed are akin to a water balance model, with scenario assessment; but the focus here is on the application of several alternative methods that detail the nature of economic activity and associated water demands in the catchment. It is unique in the extent to which it links hydrological and economic activities within an integrated catchment context. We assess the catchment economy's water demands in relation to (1) total water availability and flows and, at least in a preliminary way, (2) the value of output from economic activities. A primary objective is to demonstrate how water accounts can measure and connect the entire water cycle – from rainfall, to natural and human system flows, through to system outflows – and play an invaluable role in integrated catchment approaches for managing water and other natural resources for long-term community welfare.

Water accounts have numerous potential applications of benefit to society but they have an exceptional role in this case study by revealing the extent of human intervention in the "natural" water cycle, and the intensity and relative benefits of competing uses of water. Hence they can support decision-making about water resource allocation that is in best interests of the local catchment community and the broader regional community's economic and social welfare. In turn, this supports the selection, design and implementation of appropriate water use policies by governments. However, the research reported here in is not the end of the matter. It does not intend to present a comprehensive set of water accounts. Rather, it develops an exploratory water cycle account framework as a foundation for the ongoing development of integrated catchment research. It does this by providing data to map the structure and flows of the Little Swanport water cycle and reveal conceptual and data gaps that are limiting decisions that might bring enhanced sustainability and efficiency outcomes. Until these data gaps are filled, our understanding of this catchment will remain a work in progress.

Water accounting advances

Globally, there has been rapid growth in interest and research in water accounting. This has been part of broader efforts towards environmental resource flow accounting that can be directly tied to economic (and social) components. Resource accounting is being pursued in recognition of the fact that, if we don't measure what we have, and how it gets used, there is little chance of sustainably managing resources. Water is of particular interest in the accounting of environmental resources. Its fundamental life support and economic roles have made it subject to a great deal of tension – ranging from economic competition to violent conflict and war. Increased uncertainty about security of supply with climate change has undoubtedly increased the perceived importance of water.

While these issues are important for all nations, the effective management of water is even more critical in regions where water is scarce or supply is highly variable. Hence, there is little wonder that Australia has invested substantial resources (involving tens of billions of dollars in recent years) in improving water security and efficiency and has taken a leading role in related international efforts. The guiding principle for these efforts is the National Water Initiative (NWI) – a 2004 intergovernmental agreement across most of the nations' states and territories – being administered by the National Water Commission (NWC). The NWI is planned as an appropriate response to

the continuing national imperative to increase the productivity and efficiency of Australia's water use, the need to service rural and urban communities, and to ensure the health of river and groundwater systems by establishing clear pathways to return all systems to environmentally sustainable levels of extraction. The objective of the Parties in implementing

this Agreement is to provide greater certainty for investment and the environment, and underpin the capacity of Australia's water management regimes to deal with change responsively and fairly…
COAG 2004

The implementation of comprehensive, detailed and accurate water accounts are recognized as a vital component of the implementation of the NWI.

At the international level, water accounting is primarily developing under the auspices of the United Nations Statistical Division's *System of Environmental and Economic Accounts for Water* (SEEAW, United Nations 2006). This is part of the more generalised System of Environmental and Economic Accounts (SEEA) drafted in 1993. The SEEA is directed towards environmental-economic accounts – that is, integration of environmental resource stocks and flows and specific economic activities (rather than the direct modelling or measurement of resource flows within nature). As in the case of integrated catchment management, new approaches are responding to the need to link natural and human functions.

The aim of SEEA is to develop and compile widely-accepted and conceptually-robust physical "satellite" accounts to complement traditional national economic accounts (Australian Bureau of Statistics 2007). A range of natural resources (natural capital) which were not represented, or inadequately represented, in the standard economic accounts were identified to be subject to satellite accounting. Water is one of those resources. The long term intention is to convert the volumetric accounts to monetary ones, and hence allow budgeting of water use. At this stage in their development, scientists are struggling to construct accurate physical accounts: how much water is in the catchment, how much is in ground water, and – too often – how much is extracted and subject to evaporation as well as devoted to "economic" use? Governments who generally "own" and control water have not developed, in many places, the means of measuring use. If the physical accounting is problematic, then so must economic accounting. However, we cannot wait until the gaps are filled as decisions on water allocations are made daily – some will be the wrong decisions while other will be the correct ones, but whatever the case, luck will play a significant role due to our ignorance.

Australia's persistent and severe drought conditions, and growth in water demand, can help explain the proliferation in efforts towards water management schemes and data gathering. Examples include the Common Chart of Water Accounts, the Bureau of Meteorology data system, South-East Queensland's *Water Hub*, earlier land and water audit-based approaches (such as Australian Water Resources (2005)), and the Australian Bureau of Statistics' (ABS) water accounts. The urgency of the task has led to considerable divergence in the evolution of conceptual and data frameworks. Broadly speaking, a divide has developed between analytic approaches emphasising hydrological aspects and "natural" water physical supply and volumes or flows (with some land use factors included) *versus* an emphasis on economic supply and use as adopted in the United Nations and related ABS accounts (e.g. Australian Bureau of Statistics (2006).

The divide is closing with growing recognition of the need to understand and measure all biophysical and human aspects of the water cycle. Australia is currently working towards a set of National Water Accounts which should hopefully combine the coverage of, and help link, both approaches:
1. those leaning towards physical water cycle balance and auditing (such as the NWC's audits and "common chart" of water accounts), and,
2. the economic supply and use focus (by sector or industry) of the United Nations and ABS.

This would produce a very useful system of accounts and meet other key goals of the NWI. Our research aims to contribute to this process with a specific focus upon integration of economic and environmental aspects of the water cycle using a case study for illustrative purposes.

Uses for water accounts

To begin creating useful water accounts for a region requires thorough research and understanding of its entire water cycle's components, structure and processes. Understanding the system, and measuring it correctly (in this case, by water accounts), is the sound scientific and informational basis for all decisions for the effective management of water. Without knowledge of the iterative, complex relations in the stocks and flows of the water cycle, it is simply not possible to assess or predict intended or unintended changes that might be associated with climate, land use and cover, socio-demographics and the myriad of other natural and human conditions and influences. Hence, understanding depends on measurement. Most of the potential benefits of getting things "right" with water accounts (see the list below) are specific instances of this basic proposition.

Naturally, the understanding and data provided by laudable water accounts are integral to the National Water Initiative (NWI) and its key aim of increasing the productivity and efficiency of Australia's water use.

While many of these factors are inter-related, the benefits of water accounts include:

- The provision of detailed information on physical water use or demand classified according to standard industry sectors. This includes changes over time and can be extended with input-output and life cycle analyses to identify virtual or embodied water use for final goods and services.

- Enhanced understanding of the structure and operation of natural processes governing water availability and cycling through nature. These "supply-side" measures form the basis for determining environmental water requirements and sustainable yield levels available for human appropriation.

- The identification and quantification of all relevant linkages between natural aspects of the water cycle and human activity. This includes specific physical water demands and appropriations as well as more general overall human supply and demand effects on the flows and stocks of the water cycle. Focusing on the nexus between demand and supply for the resource provides the context for establishing water balance (or imbalance) conditions at any given point in time. It includes the assessment of the scale of human intervention in the water cycle and water quality outcomes if the relationships between human use (or land use) and natural processes are to be understood.

- Tracking and mapping the flows of water into, through and out of the economy will help identify and address water losses, leakages and wasteful human impacts. This capability is enhanced when mass balance approaches are used in water accounting, whereby discrepancies in stocks and flows can be validated and balanced to reveal losses (or data shortcomings). Areas for targeting technological and operational efficiency gains can be revealed and impacts monitored with water account data.

- The analysis of economy-wide water productivity so that those activities that provide the most return to society from water use can be identified. Ideally, the full costs and benefits of associated outputs and water supply (or use) should be known. This process facilitates water budgeting and "social efficiency" where society gets the most welfare out of defined or limited water resources (over the longer-term in accordance with sustainability principles). Commencing with the existing uses (including extractions, diversions and storages) to obtain the (marginal) value of water, we seek to determine the overall economic gain or loss resulting from small re-allocations of water – take a few litres from in-house use and apply those litres to the farm; take a few litres from growing potatoes and apply those litres to growing grapes. These are what economists call changes "at the margin". (Note that economists do not attempt to estimate the value of all the water in the world or in a catchment. They seek to make a better world, by reallocating water so that it is used in its "highest value" use.

- Identifying water productivity requires the preparation of "hybrid" water accounts where, within specific industries or sectors, physical resource use is matched to that sector's dollar output values (actually value-added). This provides a very powerful (but complex) analytical tool that can be applied to encourage the more efficient use of water so that it is allocated where it adds the most value across sectors, regions, and communities (Bain 2008). As noted by the ABS (2007, p2), "linking monetary and physical water accounts provides information useful for determining efficient water allocation, achieving cost recovery for water infrastructure assets and analysing trade-offs between alternative water and economic policies." Water pricing and trading are typically integral to implementing such change (and for these to be beneficial tools we need accurate and detailed water accounts).

- Water markets, trading and pricing - water accounts are also critical for identifying and attaching monetary values to those cost and benefits of water supply and use that are not typically covered or recovered in market transactions. There are many of these. Water has common property attributes and has historically been publicly provided so that those who use the resource do not pay the full cost of its supply and use. Externalities and un-priced effects permeate water resources use. These market imperfections have to be corrected.

- Water accounts can help assess how continued economic growth or anticipated economic and population change in different regions or scenarios will affect the water balance, services provided by water as an environmental service, and sustainability outcomes in general (Vardon and Lenzen et al. 2007). This includes variable growth rates in different economic sectors (such as housing, resource-based industry, and power generation).

- Similarly, water accounts are pivotal in determining the sectoral or regional economic implications of government water policy and exogenous influences, such as technology.

- When comprehensive water accounts are consistent and connected to other environmental resource accounts, it is possible to assess and work to optimize environmental resource use across a wide range of inter-related areas (such as linking water to energy and greenhouse gas emissions). This is a key aspect of international environmental-economic accounting.

- Water accounts that adopt system-wide material flow or mass balance frameworks also help reveal critical missing information (or what additional information would be most useful in effective integrated catchment management, and how, where and when it might be collected).

Overall, it can be seen that the water accounting process is a prerequisite for any type of modelling capability. The ideal aim is not just the sustainable use of water resources but actually increasing the social efficiency with which water is used. This presents the possibility of improving economic (and hopefully social outcomes) under a sustainable water management regime. Proper economic analysis of demand and returns from this use and of the full social costs of supply are the basis for this.

Most of the benefits of water accounts described above apply in the context of our case of the Little Swanport Catchment. DPIWE (2005) identified the following water management issues:

- potential effects of a proposed irrigation storage on river flows;
- potential effects of irrigation water usage on catchment water quality; and
- perceived lack of reliable information about the sustainable yield of catchment streams.

All these matters can only be addressed with a thorough understanding of water in an accounting framework.

Catchment-based water accounts

Catchments are special areas of the Earth’s surface. The land within their boundaries has many shared features and connections based on the simple fact of proximity. However, this spatial domain has numerous and very strong interconnections and pervasive interdependence based on its central binding essence – the collection and flow of surface water. Water together with air and soil, are the primary inputs of life and, powered by gravitational and solar forces, the water cycle's terrestrial domain is centred upon catchments.

Catchments are defined as geographic areas where water enters the system as rain and other forms of precipitation and then flows according to the topography to one or more defined endpoints or outflows from the system boundary (usually a major water body such as a reservoir, lake, estuary, bay or direct to the ocean). Catchments represent the surface where water flows under gravity, from precipitation through terrain sloping down to some lowest elevation endpoint. Their exact boundaries can be very difficult to define. However, a catchment has a boundary, its "watershed", which marks the divide between water flowing into one catchment or to another. Surface and underground water generally – but not always – coincide. The surface system is defined by topography buts need not be the case for the underground system. Cross-catchment flows occur for groundwater. Hence, we have a problem and groundwater can cause serious problems for our definition of catchments and their mathematical modelling.

The recognition of fundamental organic connections in catchments is aligned with the new, but very influential, science of ecological economics. This rapidly growing "transdiscipline" focuses upon the need for integrated studies of human economies and society firmly placed within the constraints or carrying capacity of the biophysical environment in which they are embedded. In particular, socio-ecological economics (to further broaden its title) covers all social, economic and ecological dimensions that are so important for integrated catchment management if it is to be focused upon sustainability (Cameron 1997)

Water accounting comprises an ideal way of identifying, tracking and measuring this interdependence that prevails within catchments. Catchments are natural systems with distinct and intensive fields of interrelations focused upon water. They are also near-complete in terms of input-output relations and are amenable to balancing as the books of a business are.

In accordance with the first law of thermodynamics and the mass balance property of biophysical systems, water is never lost or consumed, it simply moves across the system boundary or flows between system components or is stored within system stocks. Human influence only redirects some of these flows and stocks but may hide some of the system transfers in the export and import of water embodied in goods or via transport across catchment boundaries. In a large number of the world's catchment water cycles, human production and consumption has significant effects on both water flow quantity (mainly by storing and abstracting water from surface flows and land surface changes and water quality (by changes in land use and surface character, irrigation-soil flows, application of fertiliser and other chemicals, livestock waste, and urban and industrial emissions).

The human uses of water (call them "extractions") divert it from immediate direct contact with the environment. The routes from rain or snow to the environment are no longer unimpeded when there are extractions. Not long ago when human numbers were few and industry and agriculture were basic much water flow was from nature to nature. Today the route can be via rainwater tanks, dams, irrigation channels and, less obviously, into cultivated fields and plantation forestry, rather than on to natural grasslands and forests. The diversions and what happens to the water alters the pace of the flows and the quality of water as it comes into contact with the wide range of pesticides, herbicides, chemical fertilizers, industrial effluents and human and domesticated animal wastes.

What we can't do – although some water scientists and environmentalists would like to – is to accurately describe the region's water regime, and budget, in a state without humans (a pre-human world). This hypothetical world is what some, rather simplistically, call "the natural state". We don't know what this was. We can't recreate it with any degree of precision. We are very much left with working with what we have today. That does not mean that we cannot – or should not – restore water quality and environment flows. These things we can do, and have done very successfully in some cases. In applying economic analysis to water use, the starting point is the existing water situation – usually at a local level, or ideally at a catchment level. We can commence to estimate the benefits to be had from restoration starting from the existing situation.

In summary, catchments are very special and thoroughly deserve to be studied as entities and systems or hubs of intensive interconnections based on water processes and closely related land, ecological and human factors. Each catchment is unique with its characteristic profile of natural and socioeconomic features and its relative significance within a part of the globe. This is the theoretical background to empirical economic analysis of catchments.

The catchment regional economy

Tor Hundloe and Peter Daniels

A catchment's surrounding environment is not limited to towns and cities on the periphery of the catchment. They are included, but it is likely that a far wider, much larger economy is associated with the catchment community and its economy. That wider economy could be the state, province or nation in which the catchment sits. In the case of the Little Swanport catchment, the global environment (which includes Chinese wool buyers and the fashion houses of Milan to name two) is crucial to the economic health of the catchment and its peripheral towns. The world's best wool (some of which is produced in our catchment) is bought by buyers in Italy, to be woven into high-priced suits, skirts and cardigans. Less valuable wool, but still of very high quality by world standards is bought by the Chinese, who are today Australia's main wool consumers. Take wool growing out of the catchment and its economy would be unrecognizable – very much poorer, unless replaced by an equally profitable substitute (which could be beef and fat lambs when meat prices are strong).

Good quality meats (both lamb and beef) find their way into numerous overseas markets where, what economists call "world prices", prevail. Whether wool or meat, if you take into account the costs of transport between Tasmania and an overseas market, the local product will find its way to the highest yielding market. This means that world prices are the yardstick for many of our catchment products. Just as importantly, our case study farmers and other businesses have to pay world prices for inputs such as petrol, diesel, and artificial fertilizers. There are local products such as potatoes (heavy vegetables to transport) which find sufficient demand in Australian markets.

In what follows we will confine our analysis to the economic interdependencies between the catchment landholders and the local/regional economy. This will present a realistic and readily understood measure of the economic activity of the catchment, but keep in mind that both wool and meat grown in the catchment are destined for distant markets. In the case of wool, all the value-adding occurs overseas (for example in China, and the fashion houses of Europe). Be mindful of our fundamental task. Economic production statistics are vital for identifying the source and the extent of demand, pressure and competition for water in the catchment. They are also a major part of the water productivity indices that can be used to examine and compare various forms of output per unit of water "consumed". The economic structure of a region can be based on the physical output (e.g. kilos of wool, meat, potatoes, etc) or the related monetary value of that output (equal to physical quantity multiplied by price per unit). The latter usually receives more attention.

There is limited existing information that can be used to compile agricultural (or other economic) output statistics for the catchment. One of the best existing sources is the ABS's Agricultural Commodities: Small area data (Cat No. 7125.0) but this only resolves down to Statistical Local Areas that are too large, and cannot be made to match the Little Swanport Catchment system boundary. Some useful small-area (enterprise-level) data do exist from the 2001 and 2006 agricultural census administered by the ABS. However, they are not stored for retrieval at the catchment level and special, rather expensive customized runs would be required to estimate selected area, production and value statistics for pastures, broad acre crops, horticulture and livestock. These are only available for 2005-6. More detail on the agricultural census is available at http://www.abs.gov.au/ausstats/abs@.nsf/dossbytitle/AD7C6DD1D14FB809CA256BD000272737?OpenDocument . Note that the ABS states that "for the 2005-06 Agricultural Census, the ABS undertook a special project, with additional funding provided by the National Water Commission". This project involved coding all farm businesses to a relatively precise location, allowing for the production of estimates by customised boundaries. It is not certain whether or not this work will be continued for future Censuses." (Personal correspondence email).

Sheep, and the production of fine wool in particular, dominate in the economic land use of the catchment. While the exact number of sheep and value of wool production is not available on a year-by-year basis, it is possible to estimate the general level. One simple, fairly reliable approach is to multiply the area of grazing pasture by the dry sheep equivalent (DSE) per hectare. The latter itself varies according to the productivity of the land. The estimates of grazing land vary quite widely, depending on the source, from 19% of the total area (Resource Planning and Development Committee 2003) to 44% from the land use GIS map. Such a wide variation results from different categorisations of land and the condition of the land at any point in time, the latter being a function of rainfall and stocking rates. We rely on the GIS map and hence settle on 38 000 hectares.

Estimates of the DSE for the region vary from 1.5 to 3 DSE per hectare in the National Land and Water Audit in 2004, to 4 DSE for the region (DPIWE 2003), to 5 DSE per hectare for the best sheep farming country in Tasmania. If we adopt a likely maximum of around 4 DSE per hectare for Little Swanport, then 38 000 ha x 4 DSE = 152 000 sheep. Other indicators suggest this figure may be higher. For example, estimates based on stock water of 350ML per year based on 6 litres per day for 365 days, suggests 160 000 sheep. However, 150 000 is considerable as a reasonable maximum estimate and is utilised in the water accounting analysis later. Given that approximately 33 sheep are required for a bale of wool per year, and a bale of wool fetched $1 700 in 2007 (the base year for many of our calculations), this infers that wool production in the catchment would be around $7.7 mill per annum at this level of production and with this average price.

Potato production is a very minor activity on a catchment-wide basis but obviously important for the small number of farmers engaged in it. Production varies from a low figure of 15 hectares, and water demand is minimal. Returns to forestry are also problematic to estimate. While it has been considerable in the early days, it has not been significant recently. That is likely to change when the new plantations reach maturity.

There are few other specific data on other agricultural and economic output from the area. Existing economic statistics and input-output tables simply do not have appropriate product, spatial and temporal coverage for this purpose. Special runs on enterprise-level ABS Agricultural Census data would be a possible option for more detailed analysis.

In the Little Swanport Catchment, the human use of water is distributed across livestock pasture (non-irrigated) and drinking, forestry, limited irrigation of crops and pasture, domestic use, aquaculture and (largely non-consumptive) recreational uses.

Measuring what is produced

Economists have used, for more than 50 years now, a method of measuring what is produced, where it goes once it is produced, what inputs are used in production and where they come from to model national and, more recently (from the 1970s), regional economies. The formal name for this type of model is an input-output table or transactions table. The data are dollar values of goods and services which are bought and sold in markets. No non-market goods and services, are in the table. This means much of what is of environmental concern is not there. A transaction table captures all the (dollar) measurable flows of goods and services produced in the economy being studied, where they go, who purchases them, as well as the purchase of inputs by businesses in the economy. Not only does it model transactions within – between economic sectors of the economy – but it also captures the exports and imports of the economy under investigation. We will use this idea to capture aspects of the Little Swanport economy, such as its size and its relationships to its near-by trading centres. It is these trading centres and their businesses which flourish, or decline in response to the health of the Little Swanport economy.

It is not the first (or direct) sale or purchase in a local town that defines the value of catchment trade. For example, the money sent by catchment residents in these towns becomes the income of the townsfolk and they go on to spend (much) of it rather than put it under the mattress. A multiplier effect is in operation once an initial injection of money (this season's wool cheque) occurs and an ever-diminishing spiral of spending takes place. This flow-on benefit can be represented by output, income and employment multipliers and is calculated by mathematical modelling using the data in the transaction table.

The relationship of the economy of Little Swanport catchment to the "outside world" includes the service centres on the catchment's periphery, the Tasmanian capital city of Hobart, the rest of Tasmania, the rest of Australia, and finally the rest of the world. It is a tiny catchment in global terms but its economic reach is global, if only miniscule.

In describing the catchment economy the emphasis will be on the catchment's farmers, oyster-producers, and permanent and semi-permanent residents. They are the main source of the economic activity in the catchment. They not only provide a living (and lifestyle) for themselves, but they play a very significant role in the prosperity of the nearby towns, also in the economic health of Hobart and other Tasmanian centres. By the time wool from the catchment reaches China the economic impact (of the relatively few bales) is lost in the vastness of the Chinese economy. The multiplier diminishes quickly as soon as we move more than one step away from the catchment. This is why our focus is local.

Keep in mind the minute size of our catchment. It certainly produces world class wool, oysters and meat but none in large quantities. Hobart, the rest of Tasmania, Australia and the rest of the world would hardly notice the effect of the catchment "closing down". Even its very high quality products (such as fine wool, lamb, beef, potatoes and oysters) would still be available in significant quantities if all the producers deserted the catchment. By far the most valuable export product, super-fine to fine merino wool, is also produced in the adjacent Tasmanian Northern Midlands, and the New England district of New South Wales. Top quality and high-priced oysters destined for the domestic market are produced in nearby Tasmanian waters as well as South Australia. A different species of oyster (an Australian native) is produced in warmer climates.

The economic modelling approach that is used to trace through the multiplier impact requires an accurate recording (in monetary terms) of what is produced (for example, fat lambs, potatoes, wool), whether this product becomes an input in a value-adding industry (such as wool being sent to a woollen mill) or goes direct to consumers (as might farm produce sold from a roadside stall). The approach also requires an accurate recording of the monetary cost of all inputs to the various industries in the economy. In our Little Swanport economy the inputs are what we can call "farm supplies" (fertilizers, pesticides, fuel). From what other "economy" do these come? In our Little Swanport catchment, the closest "other economy" comprises the nearby towns (for example, Oatlands). Some inputs will come from far afield, from overseas as we discover if we trace them to their ultimate source, however there is likely to be value-adding as these products move along the chain from producer, to importer, to wholesaler, to retailer. Such is the hierarchical nature of modern economies.

The imports and exports of our catchment are not limited to the agricultural sector, as the people resident in the catchment purchase much of their foodstuffs, clothing, entertainment services and the like from outside their "economy". We should note here that many of the small-scale farmers supply their own meat and some vegetables and fruits and this has quite a significant impact in reducing their grocery bill. This will be evident when we present data on household expenditure. The goods and services purchased by consumers is termed "final demand" in an input-output model – final because the consumer is the last point in the chain, starting with growing the wheat, to milling it, to making the bread which will be consumed as toast at breakfast.

The "household sector" not only consumes but also provides much needed inputs to the catchment economy, in particular labour and human capital to the "producing" sectors of the economy (such as agriculture, manufacturing, and services such as teaching). To clarify the latter, a resident of the Little Swanport catchment who travels outside of the catchment for five days a week to teach in a school in Oatlands is "exporting" a valuable service and the catchment receives payment (the salary) for its export. If this seems peculiar, think of this teacher bringing a salary back into the catchment where it becomes part of the catchment's income.

Our next task is to explain how we model an economy. Whether it is tiny like our catchment or a great nation-state such as the US, the process is the same. Once the concept of describing economies by the construction of transaction tables was developed and governments saw what a great break-through this was in understanding their national economies, country after country undertook the enormous task of gathering the needed data, and it was not long before all industrialized countries had "national accounts" based on these data. Economic planning and policy development made a great leap from the unknown to the known. After a period of consolidation, economists and their clients (state, provincial, regional governments) adopted the process to sub-national accounts, what we tend to call regional accounts.

Tasmanian input-output tables

There was a period – from the late 1960s to the mid 1980s – that Tasmanians were well served with reasonably rigorous economic data presented in state-wide transactions tables. The whole state economy was modelled using this conventional method. Using the state tables as a starting point, it was possible to construct regional input-output tables by gathering region-specific data and augmenting the state transaction table. The Little Swanport Catchment could have been studied as a region. In this study we don't have that option as we explain below.

The most recent input-output analysis was published by the Tasmanian Department of Treasury and Finance in 1990. It was formulated using 1985-86 data. While there are often 10 year gaps in the reporting of input-output tables and hence somewhat dated data are used to interpret today's economic world, a 20 year-old analysis is not of great relevance today. Too many changes have occurred – both product prices and input prices have changed (some such as fuel, dramatically) and the structure of the economy has changed. This suggests that we are not going to be successful in modelling the catchment economy and its regional flow-on benefits.

We certainly couldn't use the conventional method of augmenting an existing state-wide transaction table. The only alternative was to build the Little Swanport economy from the ground up. With a very small economy, such as ours, this is not an impossible task. However, it is another matter to calculate the so-called technical co-efficients on which output, income and employment multipliers are based. The practicality of filling a significant number of cells in the input-output matrix (see Table 1) did not exist. It is by inverting the input-output matrix (using matrix algebra) that we can derive multipliers. We were to discover a reasonable solution to this problem as recently-derived Tasmanian multipliers were available (Julian Morison pers.comm.).

We wrote our survey questionnaire so to obtain the type of economic data we required to build our ground-up description of the economy. Our questions to catchment residents were exactly as would be asked if we were to develop a regional input-output model based on a state-wide one. We needed to know what is bought where, at what cost, and likewise what is sold where, and for what price.

An input-output transactions table illustrates the flow of goods and services – and dollars – to and from the various industries/sectors. It helps us answer the question: what is the economic impact on the surrounding towns of both personal and business expenditure by catchment residents? Catchment residents' spending money in Oatlands or Triabunna (to take two examples) goes to make these towns what they are. Their size in population numbers, the type of business which are viable in the towns, and the number of people employed in them are (in part) determined by the economic decisions made by catchment residents. Catchment residents can, for example, decide to purchase goods and services in Hobart, Sorell or locally in, say, Swansea. It is the case that some services can only be bought in the capital city Hobart. This is because that is where the businesses or government agencies exist. For example, a farmer in the catchment is likely to send a cheque annually to an insurance company in Hobart. On the other hand, the purchase of foodstuffs and a range of personal items is where considerable choice can be exercised.

The type of analysis we are discussing here is not just a simple exercise of counting the flow of dollars, or the number of workers. Economic activity is like relationships in ecology – someone's output is another person's input, and the latter's output is someone else's input, and so on in ever dwindling quantities. These subsequent rounds of activity economists term "flow-ons". As already described, flow-ons can be estimated by using multipliers derived from input-output transaction tables.

For those wishing to practise the science of economic modelling, we offer the following comments. We would use input-output analysis to describe a set of relationships in, say the Murray-Darling Basin. We would first divide the basin into a series of large regions in which significant economic activity took place, and in which there existed large towns and possibly a city. These would be areas (and regional economies) many times larger than the Little Swanport catchment. It is unusual to analyse an area as small as our catchment in input-output terms. Of course, this does not mean that this is not feasible or desirable.

We start with the basic principles. An input-output transactions table is based on data in business accounts of a firm or a farm plus data gathered in household expenditure surveys. The manner in which individuals (farmers, shopkeepers, or whatever) and their accountants gather, store and manage financial data is not directly suitable for constructing an input-output table. In the first instance, an individual's accounts have to be rearranged to show the monetary value of all outputs of the business at their destination. The same with inputs (products such as fuel). A typical farm output is a food crop which is destined for a processing plant (often far away) on its way to the consumer (final demand) in distant markets.

The individual data from a group of producers in the same business – a business can be narrowly defined as, say, "wool growers", or broadly as "farmers" – is aggregated in a grouping which forms an industry or, even broader, a sector. All the industries/sectors in the economy under analysis can be arranged in a matrix as shown in a following diagram. You will notice that the outputs of one industry are the inputs to another. For example, one of the sub-categories of a formal sector defined by government economists as “Agriculture, Fishing and Forestry” (a large and disparate sector) could be “wool production”. This output (from a supplying industry) becomes an input into the formally-defined “Manufacturing” sector (a sub-category of which would be “wool milling”). A wool mill is a “using industry” in the “Intermediate Demand” quadrant. Intermediate Demand is the step before a final product (say, a woollen suit) becomes a part of “Final Demand” in quadrant two. These quadrants are shown in the model input-output transaction table below.

Table 1 The Basic Structure of an Input-Output Table

USING INDUSTRY / SUPPLYING INDUSTRY		Row Prefix	INTERMEDIATE DEMAND: AGRICULTURE, FISHING AND FORESTRY	MINING	MANUFACTURING	UTILITIES	CONSTRUCTION	SERVICES	INTERMEDIATE SUPPLY Sub-totals	FINAL DEMAND: PERSONAL CONSUMPTION	TOURIST EXPENDITURE	GOVERNMENT FINAL CONSUMPTION EXPENDITURE	GROSS CAPITAL EXPENDITURE	CHANGE IN STOCK	FOREIGN EXPORTS	INTERSTATE EXPORTS	TOTAL SUPPLY Grand Totals
	Column Prefix		01-11	12-15	16-49	50-51	52-54	55-63	S1	D1	D2	D3	D4	D5	D6	D7	S2
INTERMEDIATE INPUTS	AGRICULTURE, FISHING AND FORESTRY MINING MANUFACTURING UTILITIES CONSTRUCTION SERVICES	01-11 12-15 16-49 50-51 52-54 55-63	QUADRANT 1 INTERMEDIATE USAGE							QUADRANT 2 FINAL DEMAND							
	INTERMEDIATE USAGE Sub-totals	U1															
PRIMARY INPUTS	WAGES, SALARIES & SUPPLEMENTS GROSS OPERATING SURPLUS INDIRECT TAXES LESS SUBSIDIES FOREIGN IMPORTS INTERSTATE IMPORTS SALES BY FINAL BUYER	P1 P2 P3 P4 P5 P6	QUADRANT 3 PRIMARY INPUTS TO PRODUCTION							QUADRANT 4 PRIMARY INPUTS TO FINAL DEMAND							
	TOTAL USAGE Grand Totals	U2															

Some supplying industries send their output to both Intermediate Demand and Final Demand. For example, a fruit grower might send the majority of his produce to a cannery while selling a small amount directly to the public from a roadside stall. By introducing Final Demand we have already gone beyond the flow of goods and services between inter-dependent industries of which there are many. There are various parts of an economy other than the farms, processors and other private enterprises that inter-relate in quadrant one.

Contributions to the local/regional economy

We now go to our case study survey data. As will be seen, the various communities in the catchment make a significant contribution to the regional economy, which is centred on the adjacent towns of Oatlands, Swansea, Triabunna, Orford and Buckland. It is in these small towns the catchment residents purchase many of the goods and services using the income they have earned from their work and production in the catchment. Let us consider this in some detail. As the various catchment communities have different needs and their spending differs, it is sensible to separate them for the following discussion. Before that, it will help to clarify a few matters pertinent to the accounting that follows.

Irregular purchases

Major items of farm machinery are irregular purchases. They are 'capital investments' in economic terms. An outlay between \$50,000 to \$100,000 is not unusual when a purchase of farm equipment is made. However, most types of farm machinery have lengthy effective (and long economic) lives. In the years covered by our survey, very few farmers purchased major items of farm machinery. For some the drought which prevailed throughout the latter half of the first decade of the 21st century, led them to postpone expensive purchases. Fortunately, the majority of farmers did not require new or replacement equipment during this period. In any case, for our purpose of constructing a bottom-up description of the economy of the catchment, major machinery expenditure would be excluded and treated as capital investment.

Stock purchases are in a different category of (generally) irregular purchases by farmers. As with farm machinery they are additions to the capital investment in the farm. Over the survey period, farmers bought and sold stock. With very few exceptions, the purchases were not significant, with the drought being a major factor influencing farmers who might otherwise have bought stock. On the other hand, there were some significant sales of stock due to the drought.

Farmers tended to fall into three groups: those whose stock purchases were in the order of \$10,000 or less per year; those who, due to the nature of their farming business or the purchase of more land, purchased stock to the value of \$50,000 to \$150,000 for each year of the three year period, and; those who purchased no stock during the period. The exception to these categories are a very small number of large farms whose owners feed large numbers of animals, and both considerable stock and feed were purchased.

Building new fences or repairing existing fences is an irregular cost for farmers; however, on all farms some level of repairs are required throughout a normal year. Fencing is a major item of expenditure. Much of the fencing work is undertaken by the farmers and hence the cost includes the purchase of materials plus the 'opportunity cost' of the farmers' labour. Opportunity cost is the dollar measure of what the farmer could earn doing other productive (paid or unpaid) work in the time taken up in fencing. For example, it is conceivable that a farmer spending a month on repairing fences might have found local government employment for this period. The foregone wages would be accounted as the cost of his work on the fence. On the other hand, there might not be any opportunity for paid work outside of the farm and the farmer would value his labour on fencing at zero dollars.

Expenses not included

A major expense for businesses (including farms) that are not owned outright but are being purchased is the interest payable on bank overdrafts and loans. Paying back the principal and interest is – or can be – a daunting cash-flow problem for the borrower. The higher the level of debt, the greater the risk to the business when poor seasons occur. The average level of debt, in the order of $200,000 for all but the very small farms, hides some extremely high debts.

From an economic accounting perspective we can exclude from our transactions table the payment of principal. This is because the ownership (where both the farmer and a bank/lender share equity in the business) should not affect the functioning of the business and its profitability. We also exclude interest payments as these are simply the transfer of some of the business profits earned by the operator and passed on to those who lend funds. That is, a farm's profit before payment of interest is the correct measurement of its economic profitability.

Lease payments

Some farmers will in the appropriate circumstances lease land. In this circumstance, the use of the land, for say grazing, is expected to provide sufficient income to the leasee to cover all his/her costs (including a wage/salary for that person), plus the amount paid to the lessor. In our survey we found an insignificant number of lease payments being made.

Farm workers

A major cost item for a large farm is the payment of permanent workers, including when employed, a manager. Wool properties employ workers at shearing and crutching times but these are contract, casual workers and in our tables are shown as such. Only the very large farms in the Little Swanport catchment engage permanent paid labour. A small number of farms are fully-managed as the owners are not residents.

A few farmers did employ workers – either throughout the year or on a needs basis – during the period covered by our survey. The range of payments was very wide and the average very low due to the vast number of farms operating without employed labour. It is not possible to report the actual dollar amounts of wage/salary payments made as the number of farms are so few that confidentiality would be transgressed.

The lower catchment residential community

The small village communities in the lower catchment have specific demands on the economies of the local towns. The relatively small number of medium-to-large lower catchment farms is not included in this discussion. The people being discussed here include owners of small residential blocks (as in Pontypool and Saltworks Road) and hobby farmers, orchardists, and tourism operators. One of the latter caters for large groups of tourists. The fact that many of the non-farming community are not permanent residents and that a significant number are retired or semi-retired residents means that their household expenditure is not high by normal Australian standards. It is further reduced by the fact that the average household occupancy in these villages is under two people.

Taking these factors into account the average household expenditure – *when landholders are in residence in the catchment* – is estimated to be $300 per household, or approximately $150 per person, per week. It is marginally higher. We have rounded the numbers to the nearest $5. Of this amount, 40% is spent in Hobart, 40% in Triabunna, 12% in Swansea, and the remainder in Sorrell and Orford in equal populations. With a new supermarket in Orford, its relative importance was starting to be noticed over the period we were interviewing catchment residents.

A significant proportion of the lower catchment landholders are not permanent residents, rather using their land (and houses on the land) for weekend and/or holiday retreats. Virtually all non-permanent landholders have their permanent home in Hobart. By converting the time temporary landholders and their families spend at their Little Swanport weekender-cum-holiday home to the equivalent of permanent residents, the total economic impact of this category of landholders can be estimated. Data gathered from these people show that on average three non-permanent landholders equates to one permanent resident; that is, 100 temporary residents equals 33 permanent residents in terms of their expenditure in the surrounding towns.

Household living cost across the total catchment

The average per adult personal expenditure (across the catchment) on usual household goods (food, alcoholic drinks, tobacco products, cleaning/washing products, health products and medicines, newspapers and magazines, and entertainment such as hire videos) has been estimated at just below $150 ($149.60). This is virtually equivalent to the per person expenditure in the lower catchment residential sub-category – differing by only 40 cents. If $150 appears low, it is important to recognize that many farmers have their own source of meat, and vegetable gardens are not uncommon, and a household comprising three adults plus a teenager would be spending between $500 and $600 per week on the listed items – not a small amount.

Households with children incur additional expenditure per child per week, although not significantly higher at a household level. This is because education expenses, children's clothing, sports items, and travel costs are not included in the estimates we are dealing with. They are included later in our estimate of overall household expenditure. Obviously the expenditure per child increases with the age of the child. Very small children add virtually nothing to the expenditure on the items we have included. A teenage child will have a noticeable impact on food and entertainment expenses. We only include the expenditure on teenage children (other-wise young adults). From our survey data this is estimated at two thirds the expenditure by adults; that is, marginally less that $100 per week.

It is important to note that for all households in the catchment a number of significant items of expenditure are excluded from the figures quoted above. They include important ones such as clothing, insurance, car registration, telephone, medical insurance, visits to doctors/hospitals/health professionals, replacement of household appliances, and other items which are normally paid for by sending a cheque to the service provider in Hobart. The other major expenditure item not included in the figure above is motor vehicle running costs (petrol or diesel, and repairs/maintenance etc). While this is a substantial cost item, and for most residents the purchases are made in the adjacent towns, the difficulty of separating private from business expenditure has caused us to include motor vehicle as a business cost.

The total amount spent on the selected items by the catchment community is arrived at by multiplying the number of permanent residents, as determined in the most recent census (August 2006), by the figure of $150, adjusting the number to account for permanent teenage residents who spend two-thirds the amount adults spend on the items under discussion, plus the expenditure by non-permanents (adult and teenage) who were not at their catchment residences on Census night, converted to full time residents.

On the basis of the average expenditure on the selected items (as enumerated above), the catchment community spends just under $4 million per annum. It is possible to allocate this expenditure to the various adjacent towns and further afield. The breakdown is shown in Table 2. Table 3 itemises the categories of expenditure.

Table 2 Expenditure by Catchment Residents on Food and Related Household Products: Location and Amount

Town	Percentage (%)	Expenditure
Oatlands	35	$1,400,000
Hobart	31	$1,240,000
Triabunna	21	$840,000
Swansea	6	$240,000
Sorell	3	$120,000
Orford	3	$120,000
Total	99	$3,960,000

Table 3 Household Items

Item	Percentage (%)
Food	50.0
Entertainment	6.5
Alcohol	9.5
Tobacco	3.5
Washing/cleaning products	6.0
Pharmacy/health products	5.0
Newspapers and Magazines	3.5
Electricity	8.5
Other	7.5

Total	100.0

As stated previously, there are various normal household costs that are not included in the above. These items in total average out over a three year period to $3,150,000 per year for the total catchment population. To not double-count the expenditure by businesses (mainly farmers and oyster farmers) on motor vehicle costs (a major item) and other expenses that overlap private and business expenditure, the amount should be reduced to approximately $2 million, which can be counted as household living expenses, rather than business expenses. As what is being described here is expenditure on services (such as telephones), clothing and appliances, most of the expense occurs in Hobart. The overall household expenditure on living costs for the total catchment is $5,960,000 (or just under $6 million per year).

Farm expenditure by various categories

Table 4 contains a comprehensive list of normal farm expenditure categories. What we have constructed from the data we gathered is a typical middle-sized beef and wool farm. It is not an average farm – given a significant difference in farm sizes and types in the catchment, the average is potentially a misleading construct. While the listed items are all essential for the successful operation of a modern farm, some tend to be more obvious and regular than others. For example, weekly or monthly fuel purchases, which are a substantial cost of farming, require a steady cash flow; so do quarterly payments for electricity and local government rates. On the other hand, numerous expenses are annual (for example, the purchase of wool packs before shearing) to be paid when the wool cheque is received. The data are based on information provided by farmers, but does not include the most severe effects of the drought in the latter part of the first decade of the 21st century.

Farm costs are traditionally divided into fixed and variable costs. The former have to be met regardless of what happens on the farm. Local government rates are due even if the farm produces nothing much of value. The same applies to interest payments on borrowed funds. The costs of various services (such as insurance, banking fees and the like) tend to be fixed. Clearly the costs of shearing, potato digging, and anything else based on quantities produced are variable costs.

Table 4 A Typical Middle-Sized Beef and Wool Farm: Expenditure

Cost Item	% of Total
Agistment	(a)..
Animal health/veterinary services	3
Contract work (eg. shearing)	14 (b)
Dog feed	..
Equipment hire	1
Fence repair/maintenance	5
Fertilizer	8
Financial	9

services/insurance/registration	
Fodder	5 (c)
Freight	3
Machinery maintenance/repairs	4
Miscellaneous	4
Pasture preparation and maintenance	2.5
Pest control	0.5
Seed purchases	3
Selling costs/commissions/ads	5
Stock purchases	7 (d)
Telephone	3
Vehicle fuel, repairs and maintenance	17
Travel	3
Rates and taxes/water	3
	100%

(a) Agistment cost could be considerable in years where it is necessary and affordable
(b) Shearing costs would be a far greater percentage of the total if the farm was mainly wool, or wool and fat lamb production. In the above example, sheep are less important than beef cattle
(c) Fodder costs would be much higher in severe drought conditions
(d) Stock purchases are very much a farm-by-farm decision, and they vary significantly depending on grazing conditions
.. Insignificant

Table 5 summarizes expenditure data for a hypothetical (representative)large farm. Note we are not discussing the largest farms, but rather a representative farm earning enough to pay $150,000 per annum for the listed items plus meet other expenditure items and earn a liveable income for an average family. We have constructed the table using the data we obtained from all farms having expenditure at approximately this level. Not all expenditure items are included and hence the total shown of $150,000 is considerably less than the grand total would be. It needs to be noted that the data on the table are based on information provided pre the severe drought.

Table 5 The Expenditure by a Hypothetical Large Farm: Per Year

	$	Percent of Total
1. Animal health (drenching)	20,000	13
2. Electricity	4,000	2.5
3. Fencing materials	15,000	10
4. Fertilizers	31,000	21
5. Finance (accounting)	4,000	2.5
6. Insurance	5,000	3.5
7. Petrol/diesel	19,500	13
8. Rates	5,000	3.5
9. Shearing	25,000	16.5
10. Seeds	2,000	1.5
11. Sprays	12,000	8
12. Stock feed	2,000	1.5
13. Transport	4,000	2.5
14. Wool packs	1,500	1
TOTAL	150,000	99

The flow-on effects

Next we turn attention to the flow-on economic benefits of farming. These are benefits to businesses that either sell to, or buy from, farmers. We will concentrate on those selling to farms – what economists call the backwards linkages – as much of the economic impact of the forward linkages (the processing of farm product) occurs outside of the regional and state economy – even outside the Australian economy. There are, as a consequence of these farmer transactions, benefits to the employees working in associated businesses in terms of wages – and simply in employment. What type of associated businesses benefit from farm expenditure depends on the nature of the good or service bought or sold.

Certain types of payments are normally paid to "head office", the capital city (Hobart). Insurance, banking, government fees fall into this category. On the other hand, a variety of purchases are sourced as close to the farm as possible – for the obvious reason to reduce transport costs. Fuel, stock feed, seeds, sprays and fertilizers will be purchased locally if they are available in the quantities and qualities the farmer wants. Not all farmers will buy at the closest source, for a variety of reasons (for example, long-running relationship with a distant supplier might be favoured because of that relationship, or maybe there are preferable payment terms). When we see the actual farm expenditure patterns for the Little Swanport catchment, it will be noticeable that factors other than local proximity are at play.

In calculating the flow-on effects of industries within our catchment, we combine all industries. The oyster farmers and oyster nursery are included with the terrestrial farmers. They are all farmers. Given confidentiality requirements we cannot discuss the three oyster farmers as a separate category. A guide to the importance of the oyster industry is to think of it as being equivalent to three large terrestrial farms. We will discuss the oyster industry in a little more detail later.

We have selected major items of farm variable costs (excluding household purchases which we have discussed previously) and show where they are sourced (Figures 1 and 2). The items shown in the table account for over 40 percent of farm total costs. Major items excluded are contract shearing, stock purchases, selling costs, machinery repairs, financial services, rates and insurance – these account for over a third of total costs. All these expenditure items, plus the remainder are included in Table 6.

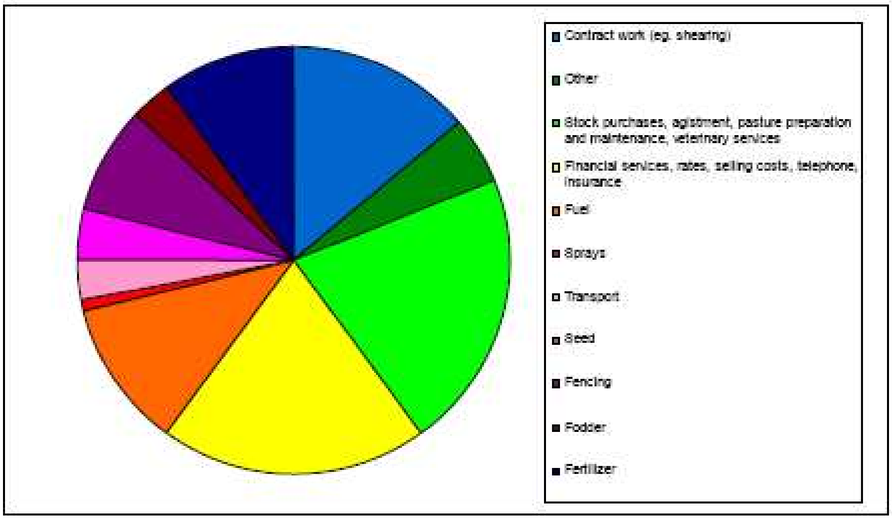


Figure 1 **Categories of Farm (inc. Oyster Farm) Expenditure: Percentage**

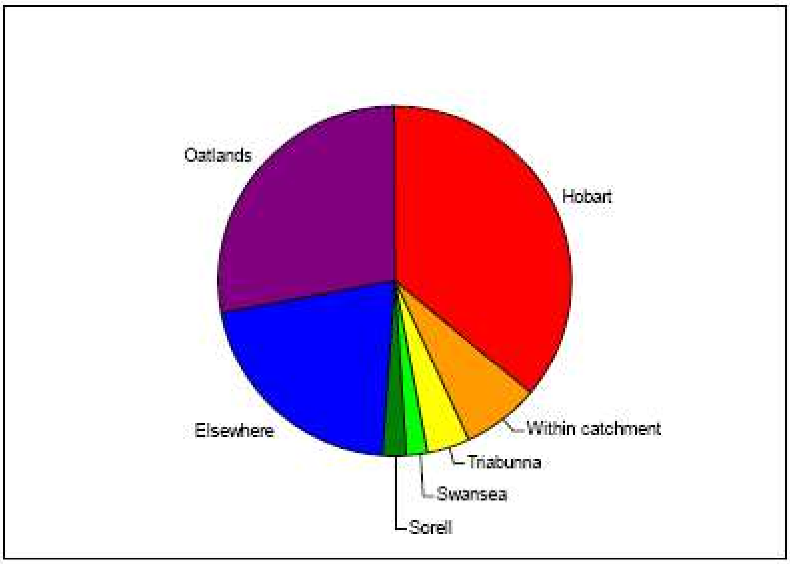


Figure 2 **Farm (inc. Oyster Farm) Expenditure by Place of Purchase: Percentage**

Caveats

It is important to note that the expenditure data we are presenting represents a snapshot averaged over the three years 2003-04, 2004-05 and 2005-06. The data are not necessarily for a "normal year" – whatever that concept implies. The data do not cover the extreme drought conditions which gradually developed in 2006 and became obvious in economic terms in the 2006-07 year. As a consequence of excluded drought years, substantial "defensive expenditure" by farmers is not included. This would include the purchase of stock feed in 2006-07, and ongoing since then. Defensive expenditure is an economist's term to describe paying money to either attempt to "drought-proof" a farm, or to compensate for the effects of drought by purchasing fodder (or, if possible, water). Various other recent changes have occurred. For example, fuel prices have kept on increasing; the price of grains, wool and meats has increased substantially; but so has the cost of fertilizers. Other than fuel price increases, the three oyster farms (oyster and spat producers) have not experienced any significant changes in the costs of inputs or the price received for product. By the nature of their operations, they have not been adversely affected by the drought.

Given the vagaries of nature and markets we must be circumspect in the use of the above data in making generalisations. For example, fertilizer application (which is shown as a major cost) varies significantly depending upon the types of crops grown (if any) and the nature of sheep and cattle runs, such as the extent of improved pasture in comparison to "run-country". The data we gathered from individual farmers shows that even in years where there is not a significant variation in climate and/or gross income, fertilizer applications can be quite variable. There are circumstances when a particular farm will need to apply out-of-the-ordinary quantities of fertilizer, notwithstanding external factors. In fact, examples of this were found in our survey data. As a conservative strategy we excluded out-of-the-ordinary expenditure (which occurred within the three year period) when reporting the information shown above.

The other thing to note about averages is that the extent of the range in the amount spent, from the farm spending the least to the one spending the most. This can be (and is in our survey data) quite a significant range. As we have a small number of large farms (spending considerable amounts on a mix of inputs) we find the average is being pulled up from what it would have been if only the smaller farms were represented. On the other hand, the large number of small farms spending small amounts on most inputs pulls down the average.

There are very significant differences in the size of farms in the catchment and this becomes obvious in the expenditure data on a farm-to-farm basis. Expenditure is not a linear relationship between size, mainly due to the fact that larger farms and businesses generally have easier access to financial resources (that is, they find it easier to borrow and spend). There are also differences between the amounts of some inputs used on the lower catchment farms compared to the upper catchment ones. For example, the lower catchment farms require far less application of sprays (weedicides, etc), as there is not as much weed infestation in this area compared to parts of the upper catchment. It is important to note that not every farm or business has to purchase every item from the lists. A weed-free farm would not need to use herbicides. In good years, most (maybe all) farms would not need to purchase stock-feed. Rainfall can vary greatly between properties – this was very evident in the data we gathered from individual farms – and hence productivity varies significantly. Then there is the human factor. Farming is a very individualistic enterprise. Differences in the quality and quantity of products – and profits earned – are inevitably related to the skills and attitudes of the individual farmers. Farm management skills influence the amount spent on farm inputs, as much as the market value of outputs.

We aggregate the data on farm expenditure, the data on expenditure by the oyster-growers, plus the data from across the catchment on personal living expenses (the latter estimated previously at $5,960,000) to show the aggregate economic impact that the catchment residents and businesses make on the local towns. This is presented in Table 6.

Table 6 Totality of Expenditure by Catchment Residents: Year

Buckland	*
Hobart	$7,205,000
Oatlands	$4,500,000
Within Catchment	$750,00
Triabunna	$1,312,000
Swansea	$409,000
Sorell	$320,000
Orford	$120,000
Elsewhere	$2,344,000
Total	$16,960,000

* under $100,000

As discussed earlier the totality of economic input does not cease with the expenditure in the local towns, Hobart or elsewhere. There is a flow-on (multiplier) effect. For every $100 of purchases in the local towns by catchment residents, the local businesses (such as the stock and station agents) must expand output (from what it would have been had not the catchment people gone to them), and next their suppliers also have to expand output in an ever dwindling chain. Multipliers can be calculated for output, income and employment to illustrate the impact. We estimate that in the order of 150 jobs exist in the adjacent towns due to the business they get from the catchment, and there are about 70 jobs in Hobart. This means that – at a minimum – there are 220 jobs created by the production in the catchment. This equates to approximately one job outside the catchment for every one job in it.

We have described the regional economy the best we can with the data available from our survey, and given the fact that there are no longer formal input-output transaction tables for Tasmania (a major impediment to what should be a simple mathematical exercise). What we have not done is delve into the use of resources, in particular water, in our catchment. This is our next issue.

The Little Swanport water accounts

Peter Daniels and Tor Hundloe

"Water is always in circulation, moved in its various forms between phases and between locations"
Leaman, 2005, p10

The major task at hand is to present an appropriate water accounting framework for the Little Swanport catchment and to populate this framework with data where available or capable of being estimated from related or proxy statistics This water accounting research has been moulded around the water cycle within Little Swanport Catchment and is undertaken in order to understand and measure the flows and interactions of water in the catchment, extending to its estuary.

As discussed, water accounting is undergoing fervent developmental efforts across a diversity of institutions and the "state-of-the-art" will evolve rapidly over the next decade. The framework developed for this project is offered as a step to aid this process and to help address the more immediate short-term concerns and pressures for socially-efficient decision-making about managing water resources in the catchment. As discussed earlier in this chapter, one of the main potential benefits from water accounts (when capable of being matched against broader socioeconomic information systems), is their contribution to water budgeting and productivity assessment. This means that water can be put to uses that have the best welfare outcomes for society (when all cost and benefits are included). Water productivity tends to rely on measuring this welfare in terms of dollars but the idea can be extended to wider social and economic effects.

We describe the water accounting framework developed to provide appropriate and effective measurement and tracking of water stocks and flows in Little Swanport. This framework will be generic in terms of outlining a "template" that integrates the best and most relevant parts of several water accounting systems which currently exist or are in development. While the model generated represents a blend of several approaches, it builds upon the essential logic employed in the Australian Water Resources (AWR) (2005) water cycle and balance assessment approach as utilised by the NWC (see www.water.gov.au). However, the framework presented is also customised in another sense – it only covers and focuses upon a subset of the most relevant features and activities that influence water use and demands in our particular study area. It is also important to reaffirm that our water accounting framework is experimental in nature, a "work in progress", and, like most activity in this relatively new but critical area, it is likely to evolve and improve rapidly.

Knowledge of the economic structure and nature of human land use of Little Swanport Catchment is vital for accurately and usefully describing the area's water cycle characteristics and hence the structure and appropriate focus and coverage of the water accounts. These aspects have already been described in some detail. The Little

Swanport catchment is predominantly rural/agricultural in character with a significant "natural" area component. 44% of the total surface area of the catchment is classed as "grazing modified pasture" or "grazing natural vegetation" and an additional 11% is "production forestry". Approximately 44% of the area is also conserved as relatively natural areas or exists as "residual native vegetation". However, much of this land has been affected by humans at some stage over the past 200 years (for example, logging and at least partial clearing).

Water accounts for the catchment must be guided by its agricultural, rural character. The agricultural land, and even substantial tracts of the residual native vegetation areas, involve human clearing of original forest and other vegetation; stock habitation; other land cover and terrain modification; abstraction, diversion and storage of surface water flows and (very limited in our case) irrigation; and release of water back to the ground and evapotranspiration. It is important to note that not all of these activities relate directly to water use in the catchment. There is some water "flooding" into the catchment from Hobbs Lagoon, a human-made water storage, but the water is drawn from the neighbouring Prosser River Catchment. The land use and economic production analyses have provided vital inputs into the process of compiling the catchment's water accounts.

The water cycle and water account framework – logic and structure

The basic guiding structure of the "natural" water cycle and human intervention in this cycle is depicted in Figure 3 below. This structure is consistent with most major water accounting frameworks that include both environmental and economic dimensions of the water cycle. In particular, the scheme aligns with the Australian Water Resources (AWR) (2005) water cycle or balance assessment. However, the approach explained has been tailored to the nature of the Little Swanport Catchment and provides a useful and novel basis for the integrated water accounts which is required for understanding and measuring all relevant processes in our study area.

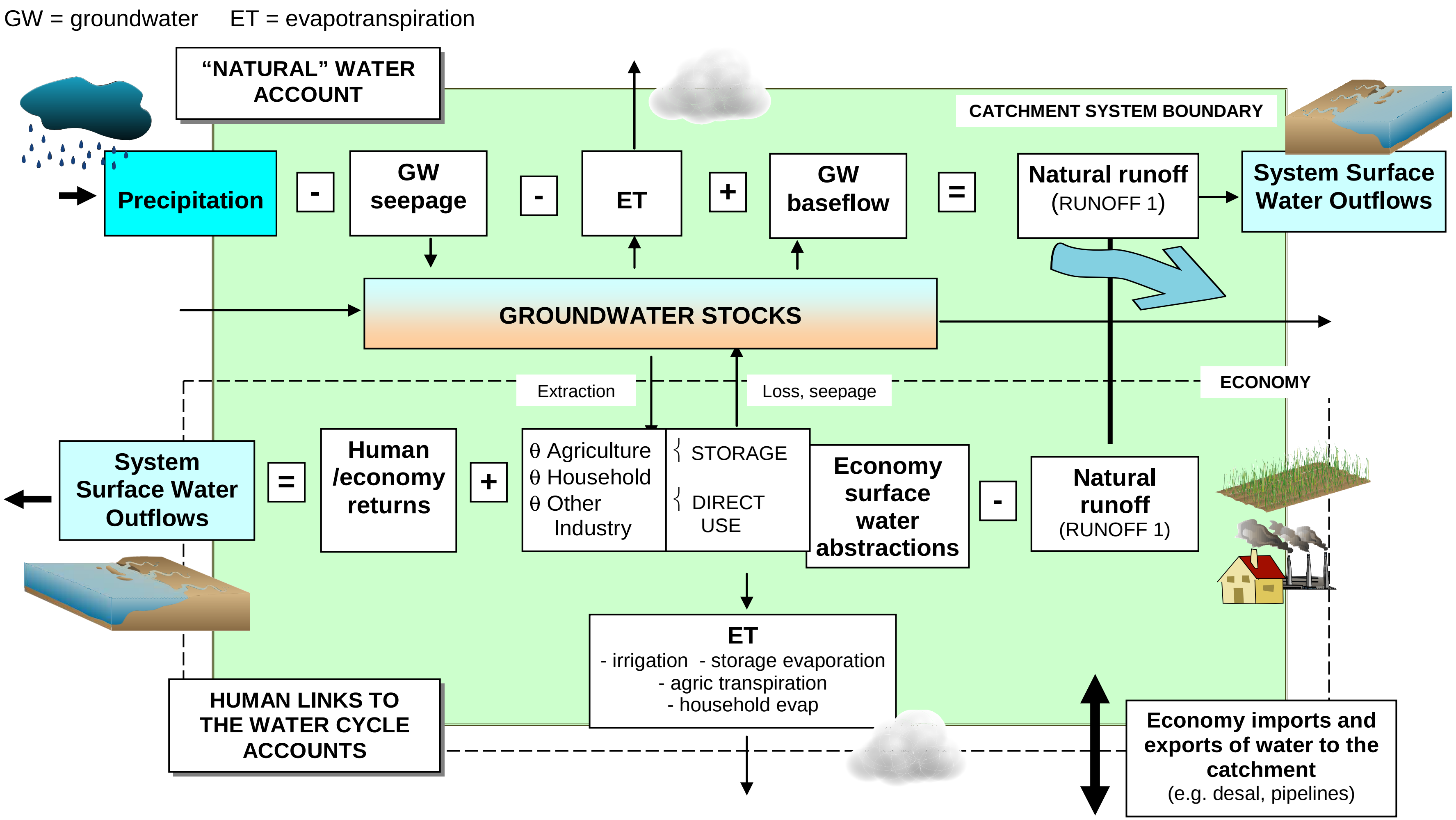
Without humans, the natural water account would be comprised primarily of surface water runoff flows fed by precipitation. Precipitation enters into soil water and groundwater, and surface flows can be fed by groundwater baseflow back into streams and rivers. Major losses between precipitation and watercourse surface flows exiting the system also occur by evaporation from the ground surface and all surface features, as well as evaporation and transpiration (through natural vegetation) from soil water. Non-human animal life uses water taken up by plants (or other animals) and may also divert surface water flows by drinking. These quantities are likely to be very small in the overall water cycle.

The basic water cycle equation for the natural water cycle is (from left to right in Figure 3 :

Precipitation – Groundwater – Evapotranspiration + Groundwater = Surface Runoff
seepage baseflow

Beyond the inflows and outflows from precipitation, groundwater can involve cross-catchment flows that do not follow the terrain restrictions of catchments. While it provides an important medium taking and returning from catchment surface water, it often has independent sources and releases across the system boundary. There is also the sizeable storage and movement of water in soil to consider. Water also enters and leaves the system, as water vapour and there can be very substantial flows of (usually) salt water into the catchment boundary via the estuary. These flows are ignored in the water accounting framework presented here because for most of them there are no data and the cost of getting reliable data would be excessively high. While something is lost due to these gaps in knowledge, much is achieved by the modelling we can do.

Figure 19.1 A Simple Water Budget Framework for Catchment Water Accounts

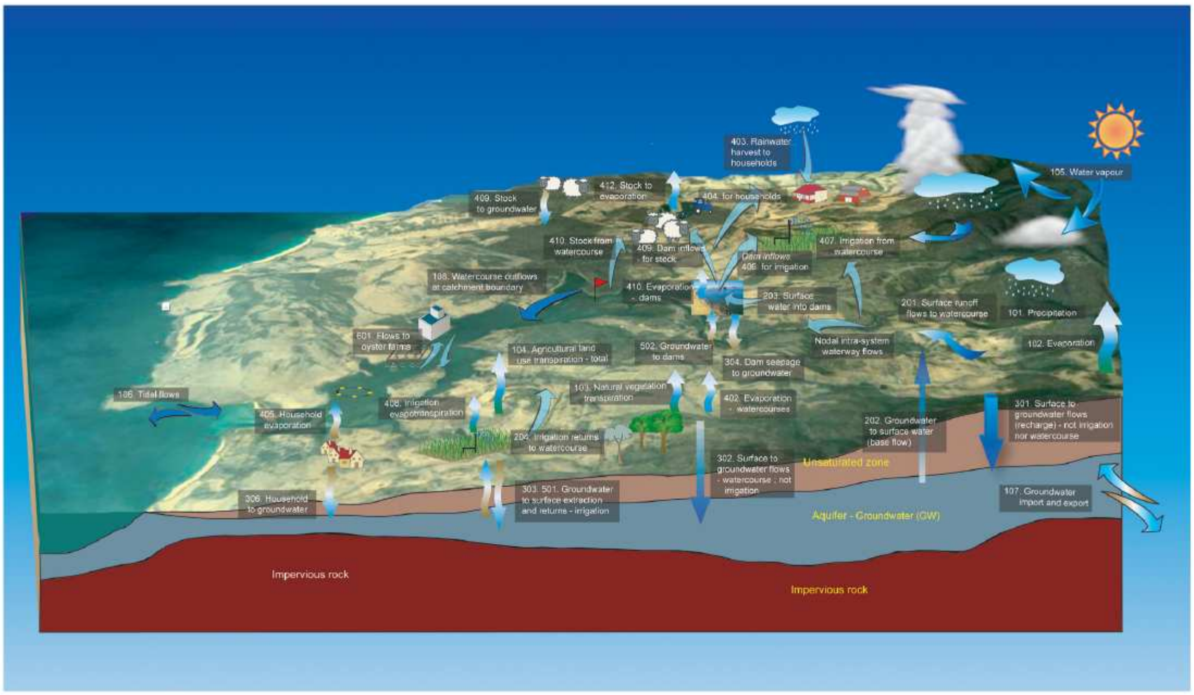


Note : "Natural" evapotranspiration and groundwater flows will be affected by human land use and extractions

When human activities are included (from right to left in the lower half of Figure 3) we have the human abstractions from surface water which are either returned (often with quality change) to surface water, or evaporate from irrigation surface water or household and industry use and release, or are transpired by agricultural biomass. Humans also extract and return water to groundwater and can build structures to import and export water from outside the system (for example, from Hobb's Lagoon) or the boundary of the Little Swanport catchment in the south-west.

The simple water budget concept presented in Figure 3 contains the logic and structure used for the detailed water account framework (and initial data population of this framework) described in the next section of this chapter (see Table 7). While our Little Swanport accounts draw heavily upon the approach adopted for the Australian Water Resources (2005) water balance assessments, they incorporate greater integration of economic and natural environmental aspects and provide different emphases in view of the specific characteristics of the catchment. That is, relatively high levels of "natural" land cover (over 40%); an economy and land use pattern, and water demands, dominated by rural-agricultural activities; and a very small population (521 permanent residents) and low levels of household and other industry activity and water demands.

The main components in the Little Swanport Catchment water accounts prepared for this study match and extend upon those provided in the simple framework in Figure 3. In line with the economic conditions of the catchment, the Little Swanport accounts elaborate upon farm water aspects such as farm dams, and irrigation abstraction and loss but have little detail on residential and other industry system components. The conceptual diagram in Figure 4 graphically identifies the major relevant water flows that are the focus of the detailed water accounts introduced in Table 7. Unfortunately, we are limited to using data from some years ago, 2002-2003. There are not comprehensive figures for later years. Notwithstanding the extensive data we gathered from farmers and other landholders during the many visits we made to the catchment, the measures of water use in what was a dramatically changing period – from good rains to extreme drought – were clearly not representative of more normal periods. Hence we rely on research data in a much more stable climatic period. For the purposes of consistency, all estimates are derived from sources as close as possible to this financial year we are using. Unfortunately, we are limited to using data from some years ago, 2002-2003. There are not comprehensive figures for later years.



Codes match Table 19.1 detailed water accounts

Figure 4 **Little Swanport Water Cycle Conceptual Diagram**

The water accounts applied to the Little Swanport context do take on some of the accounting features required for mass or material water balancing. This is essential for the long-term accuracy and usefulness of such information systems. However, inadequate data (especially regarding groundwater stocks and flows) has prevented the application of this logic to the available or derived statistics. In line with the mass balance approach, the Little Swanport Catchment water accounts (LSCWA) begin with the system's **opening storage balance** for water. These stocks include natural and human stores of water. In our case study, farm dams are important but there is no accurate information on the level of actual storage at the accounting commencement date. Ideally, this is mid-2002 but the timing of the account data across all the different components varies substantially.

The next section of the LSCWA identifies all the major **inflows and outflows across the system boundary** (that is, the catchment watershed). This includes precipitation into the catchment, evaporation and transpiration, water vapour movements, flows from the sea and other sources outside the catchment. Separate measures are assessed for flows under human influence such as evapotranspiration for agricultural land and irrigation, stock and domestic or household use, and the transport of water from outside the boundary. The next four sections break down the main inflows and outflows between relevant components in surface water and groundwater.

Inflows to surface water include flows from runoff and streams and rivers into storages. Natural and human aspects of surface water flow are covered. The major component quantity is, of course, runoff into watercourses but the other major natural inflow is discharge from groundwater. Human-related surface water transfers include surface water flows or extractions into farm dams and returns back from the economy to surface water include those from irrigation, households and other industry. Tidal inflows can also be classed as surface water inflows but these measures obviously involve significant qualitative and energy issues and are not measured here.

Inflows to groundwater are comprised of natural and human sources. Natural augmentation of groundwater can come from pervious land surfaces and watercourses and from aquifer/groundwater movements from outside the catchment. In the catchment, inflows to groundwater are likely to include those from seepage from irrigation, dams, conveyance channels and households and any other industry.

"Intra-system nodal flows" have been added to the scheme to acknowledge the importance of the spatial distribution of water availability and use. Accessibility to water is a major factor in determining effective availability. While there is very little information available on supply and use at disaggregated levels within the catchment, more specific flow (and stock) accounting measures that are geo-coded and analysed within a spatial context will undoubtedly be essential aspects in future water modelling and strategic planning.

As we move into examining **outflows from surface water**, many flow measures from other parts of the framework reappear on the list as outflows from one medium and are often inflows into others (for example, flows into groundwater are often losses from surface water). The losses from surface water via natural means are mainly via evaporation from non-anthropogenic surface water features and watercourses and seepage to groundwater from water bodies. A major loss from most catchments can have a human dimension. This is the flow of water from watercourses at the system endpoint boundary (often a major water 'reservoir' such as the Little Swanport estuary in our case study). In the surface water outflows section we find the most detailed analysis of abstractions and water returned to the economy as this is typically the primary source of water for human use.

Economic withdrawal of water can be classified many ways such as self-extraction versus centralised or "distributed" water such as the mains supply in most Australian cities. This division is then often split across various industry types or sectors. In Little Swanport, there is no distributed water from centralised storage and treatment facilities. Hence, the accounts focus upon self-extracted water across the main consumption sector, and from the major storage entities – agricultural water use from farm dam storages. The surface water accounts track water transfers into dam storages. The outflow accounts measure irrigation, stock and domestic and household water use by surface water source (dams, direct watercourse extraction, rainwater harvesting and groundwater) and sometimes institutional type (e.g. licensed or unlicensed). Often as a subset of these uses, losses from the catchment system are also specified in the form of evaporation from dams and other built infrastructure.

A similar structure is used for **outflows from groundwater**. Nature-based outflows include discharge to watercourses, springs and evapotranspiration (the last is not included as part of overall evapotranspiration from the unsaturated soil zone). Economic extractions are primarily direct to dams for irrigation or stock and domestic use (and possibly household and other industry use). Groundwater use for economic purposes is minimal in Little Swanport, as we have not been able to ascertain the extent of ground water in the catchment.
Section 6 of the detailed water accounts in Table 7 shows the various main economic sectors and water volumes by supply sources and losses and exports from these water activities. It is primarily a reorganisation of measures from economic abstraction and returns in other parts of the accounts, grouping the information on sourcing and release by pastoral and cropping, household, forestry and other economic activity.

The closing balance section is presented to preserve the ideal mass balance approach for the accounts but, as with the opening balances, there are insufficient data to do so with the degree of accuracy we would like.

Preliminary water accounts for Little Swanport

In this section, we add data to the water accounting framework developed and discussed in the previous section. The water account data is incomplete and is based on a mixture of existing specific information for the required items and estimates or derived statistics based on related or proxy data. Hence, it is important to stress the formative and provisional nature of the Little Swanport water accounts presented at this stage.

The rural and agricultural basis of the catchment has guided the detailed structure and focus of efforts at populating the water accounts. Natural aspects of the water cycle and agricultural water demands by humans are anticipated to dominate. Agriculture is the major user of water in Australia and made up 65% of human water consumption in the country in 2004-5 (Australian Bureau of Statistics 2006). This is slightly lower for Tasmanian agriculture which comprises 59% of the State’s human water use. Overall, Tasmanian households consumed about 16% of the State’s water and manufacturing (primarily the wood and paper products industry) is responsible for around 11%, with other uses being minimal.

For our Little Swanport accounts, urban and industrial water accounting aspects are relatively insignificant and the specific framework is most suited to regions dominated by agricultural land use and farming. For example, there are few account items, and no data, for regulated or unregulated discharges which would be critical parts of the water cycle in an urban-industrial context. Notwithstanding the agricultural–rural focus of our accounts, the overarching structure that we have developed is based on inputs from a multidisciplinary team of researchers, and the detail and emphasis could readily be adapted to other regional economic structures where farming was less dominant.

As discussed, water accounting is undergoing fervent developmental efforts across a diversity of institutions and the "state-of-the-art" will evolve rapidly over the next decade. The framework developed for this project is offered as a step to aid this process and to help address the more immediate short-term concerns and pressures for socially-efficient decision-making about managing water resources in the catchment. One of the main potential benefits from water accounts (when capable of being matched against broader socioeconomic information systems), is their contribution to water budgeting and productivity assessment. This means that water can be put to uses that have the best welfare outcomes for society (when all cost and benefits are included). Water productivity tends to rely on measuring this welfare in terms of dollars but the idea can be extended to wider social and economic effects.

Unfortunately, data limitations are formidable in attempting to populate the water account framework for Little Swanport. There are some specific and quite reliable sources of information and these tend to focus on data for 2002-3. Hence, this period has been adopted as the focus of the information collection process despite the important fact that many of the major resource allocation issues stem from the drier conditions that have prevailed and intensified since 2006.

One of the major sources of good information on selected aspects of the Little Swanport water cycle is SKM's (2004) Little Swanport River Catchment: Water Balance Model and Scenario Assessment report which was carried out primarily as support for the Water Management Plan and to identify environmental flows and suitable entitlements and use in view of the availability of water resources within the catchment. SKM acknowledge that data are limited or not available for several important stores and media flow – for example, soil water and river channel volumes. Little is known or recorded about ground water flows. It is important to note that water stocks and flows do not occur only at land surface and subsurface levels but via the atmosphere and, potentially, from the oceans. This recognition introduces new system boundary issues and potential accounting extensions but few data exist at present. Hence, data timing and availability are just too restricted to take on the laudable but ambitious goal of mass balancing of regional water accounts. This goal will, and should be, an ultimate objective for accurate and comprehensive information for sustainable water science and planning.

These data and coverage shortcomings are acknowledged in the compilation of the Little Swanport accounts presented here. However, the overriding study aim is to help make progress in the conceptual development of useful water accounts at this level. A key part of this process is to identify how to improve the structure and content of the accounts and their specific items and to identify informational gaps and possibilities, and potential options for the estimation of empirical data.

As with most water accounting systems, the accounting framework presented here makes minimal differentiation in terms of water quality even though water quality impacts are a key aspect of the broader goals of the report. Relative and total water flow quantities involved with different economic activities and land uses can help directly assess the potential for water quality impacts at different locations and times in the catchment. More specific measures and incorporation of water quality concerns will be vital in the future evolution of water accounts.

Before we take a closer look at the overall and specific water account data for the catchment, it is appropriate to reiterate that a major although small scale irrigation source of water in the catchment has been Hobbs Lagoon. This water is sourced from outside our Little Swanport Catchment system boundary (in the Prosser River Catchment) and its related inflows and outflows have been ignored, for practical purposes in the water accounts though, technically, they should be included as system imports and exports.

First, if we consider just the overall, aggregated flows in the Little Swanport water cycle, the primary components are:

- precipitation (500 GL)
- evaporation (213 GL)
- transpiration (155 GL)
- groundwater recharge (24 GL) and returns (6 GL) within the system (and ideally groundwater imports and exports through the system (unknown)), and,
- surface water outflow from the system (approximately 113 GL).

The **simple annual water cycle equation**, with crude data for the study catchment, becomes:

500GL - 213GL – 154GL – 24GL + 6GL = 113 GL
(Precip) (Evaportn) (Transpiration) (Recharge to GW) (GW to baseflow) (Surface water outflow)

This can be conceived as a representation of the "natural" water cycle though, as discussed it is not possible to clearly depict the natural regime given that humans have markedly altered the catchment landscape via land use changes. For example, around 50% of the catchment surface vegetation and cover (and soil and runoff conditions) has been modified for grazing and other economic purposes and significant remaining sections have been impacted by humans at some time in the past. Human consumption of water (calculated as around 5GL per annum) is not identified within this general breakdown but would be partly accounted for in the total evaporation and transpiration levels.

The approximate precipitation level has been derived on the basis of a range of existing catchment rainfall and area estimates that yield between 360 and 565 GL. This equates to around 570mm average annual rainfall across 880 sq kms. Once again, it should be noted that drier conditions ensued after this accounting period (around 2002-3). In the absence of superior sources of information, the estimates for evaporation (at 43% of rainfall) and transpiration (at 31% of rainfall) are subject to much uncertainty and have been based on generalised parameters from water budgets for the Border Rivers-Gwyder region in NSW (Border Rivers-Gwydir Catchment Authority 2008). They have been adjusted in accordance with estimates of 10% runoff revised up to the relatively reliable 22% runoff derived for this catchment (113GL of 500GL). This annual outflow measure is based on results presented in DPIWE (2003). It is derived from data for 1971 to 1990 and is unlikely to represent low-flow periods of recent years. Some more detail on estimates for overall levels (and most account items) is provided in the notes column of Table 7. Based on the pattern of land use around 50% of transpiration (77GL) is estimated from "natural" land use areas and 50% from agricultural and other human-influenced land. Catchment-wide inflows to groundwater are proposed as 3.5% of total rainfall with 25% of this groundwater seepage returned to surface flows. Sources for these estimates are provided in Table 7. The balance (after evaporation and other losses) is considered as surface runoff into major watercourses and the average annual estimate utilised here is approximately 113GL of surface water outflow into Little Swanport estuary (DPIWE 2005). These overall water cycle accounts do not include tidal flows into and out of the estuary nor the (negligible) human-based imports and exports of water such as desalination, bottled or water in tanks, and pipelines.

The detailed water accounts in Table 7 provide data, where available, at a more disaggregated level and focus upon the supply and use of water for economic and household purposes (predominantly agricultural activity and farm dams). The logic and structure of this table have been described in the previous section. It is not necessary to discuss every individual data entry in the table. Only selected statistics will be presented when they are of particular interest or relevance to the overriding aim of the report – the extent and significance of competing uses of water in the catchment. The most relevant data is summarised in section 6 of Table 7 ("Use of water (by supply and release)".

The accounts table is comprised of six sections and opening and closing stock balance sections. In addition to the opening and closing balances, the six sections are:
1. Major inflows and outflows to the system (catchment)
2. Inflows to surface water
3. Inflows to groundwater
4. Outflows from surface water
5. Outflows from groundwater
6. Use of water – by supply source and release type

As discussed, section 6 of the water accounts is primarily a reorganisation of other accounts in the table in order to facilitate the overall analysis of human intervention in the catchment water cycle and the relative use and impacts of competing uses. The opening balance stocks have been discussed previously and data estimates for this aspect are unreliable given lack of information about the capacity of natural reservoir and human storages at the start of the reporting period, and no useful information about groundwater stocks. What is known is that the reservoirs of the water in the catchment were predominantly created by humans. In 2002-3, there were approximately 1,200 non-flowing freshwater bodies in the agricultural part of the catchment and the SKM (2004) analysis suggests that total storage capacity was approximately 10,700 ML. For licensed water entitlement storages, only around 392 ML of the 4,100 ML of storages, mainly from Hobbs Lagoon, were fed from water from the Little Swanport catchment. These estimates were based on models that convert dam surface areas to volume. Non-license farm dams had a total capacity of around 6 3000 ML. Hobbs Lagoon acquires its water from the neighbouring Prosser catchment; however, impediment structures divert 'flooding' of water into adjacent areas of the Little Swanport Catchment, although this input is generally minimal. How valuable this flooding water is, is a moot point, but as it is not associated with extreme agriculture in the catchment we neglect its influence in our accounts. Human imports and exports of water across the system boundary are effectively zero and there is no information available on cross-catchment groundwater flows. Only Hobbs Lagoon confounds what is a very simple catchment.

In Section 1 of the accounts in Table 7, the major inflows and outflows to the catchment cover most of the major statistics used for the overall water cycle and simple annual water cycle equation presented above. The only additional information it contains is:
(1) the 3.45 GL loss/export of water from the system due to human water use from households, irrigation, dam surfaces and stock and domestic use (excluding that from evapotranspiration of precipitated water from agricultural and other modified land use)
(2) the import and export of water vapour across the aerial system boundary (estimated at 4 100 GL on the basis of Tasmanian data compiled by Dunlop (2003), and
(3) tidal flows into and out of the catchment (of seawater) are estimated to be 325ML per day (or 119 GL per year)

Table 7 Preliminary Little Swanport Catchment Water Accounts

Sources (shown in notes column) : *S1 = SKM (2004) S2 = Border Rivers - Gwdyr (2008) S3 = AWR 2005 Macquarie Water Cycle report S4 = Dunlop (2003) S5 Bureau of Rural Sciences S6 = Little Swanport land use map GIS S7 = DPIWE (2003) S8 = Resource Planning and Dev Comm S9 = Meyer (1997) S10 = DPIWE Tas (2005)*

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			OPENING STORAGE BALANCE		
	N & H		Major on-river reservoirs (includes dead storage volume)		
	H		*On-stream minor and farm dams (unknown, record as zero - assume same at start and end of period)*		
	N & h		*Major off-river storages (includes dead storage volumes)*		
	H		*Off stream minor catchment dams*		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
x	*H*		Water entitlement water storages - licence	**4100 ML** **392 ML** (fed from Little Swanport catchment)	Most of this water is in Hobbs Lagoon and not drawn from LS Catchment. Calculated from storage allocation for current entitlement (3846ML) adjusted up given 90% demand use; 2002/03 (S1) * Based on current use - licence withdrawal to dams reduce flows only by about 191ML/yr for stock and domestic only (so relevant volume 191/0.5=392ML). Entitlement basis = 689ML/0.5 = 1378ML
x	*H*		Farm dams - non-licence	**6300 ML**	Based on total capacity. Unknown % full. From SKM (2004)(S1) Farm dam analysis * Around 1200 non-flowing freshwater bodies in agric part of catchment (in 1999/2000) - p36 DPIWE * Dams reduce annual flows by around 4760ML
	N		*Renewable non-saline groundwater (< 3500 mg/l)*		Fresh divertible groundwater stock - very crude estimate 8.6GL as 22% of 39GL (S4)
	N		*Renewable saline groundwater (usually zero)*		
	N		*Non-renewable groundwater (capable of being mined)*		
			Total opening balance		
x			**1. MAJOR INFLOWS AND OUTFLOWS TO THE SYSTEM (CATCHMENT)**		

Added to SKM - AWR (2005) model	***Nature (N) or Human (H) Influence***	**LS Code (see Fig 4)**	**Account Item**	**Estimate for Little Swanport Catchment**	**Notes**
x	**N**	**101**	**IMPORT** Rain/snow/ice melt to surface	**500GL** (Assumed from a range of 360 - 565 GL)	Are variable estimates of the actual LS catchment area 610 - 898 sq km. **360GL** calculated as 610 sq km (DPIWE 2003) x 591mm (600-800mm rainfall in other estimates) * BOM mean = 630mm in 2002 (se RPDC 2003) but lower than normal since 1970; 630mm x 898 = **565GL** Catchment Area : **898** sq km (LSCC 2002); probably includes outlets beyond main study
x	**N**	**102**	**EXPORT** Evaporation - excludes transpiration; excludes small human use component	**213 GL**	* 43% of rainfall based on adjusted info in S2 - with 22% runoff vs. 10% * total evapotranspiration = 68% of rainfall based on S3 ; 31% + 43% = 74% based on S2
x	**N**		**EXPORT** Transpiration	**154 GL**	* 31% of rainfall based on adjusted info from source S2 - with 22% runoff vs. 10% * covers natural vegetation and human modified land use
x	**N**	**103**	Transpiration - natural vegetation	**77 GL**	Based on land use - 50% of land (S6) and 32% of rainfall evapotranspired (S2)
x	**H**	**104**	Transpiration - from agricultural land total	**77 GL**	Based on land use - 50% of land (S6) and 32% of rainfall evapotranspired (S2)
			EXPORT Other human evaporation or transpiration - includes evap from households (405) + ET/loss from irrigation (408) and stocks and domestic water use (411) and from dams	**3.45 GL**	

Added to SKM - AWR (2005) model	***Nature (N) or Human (H) Influence***	**LS Code (see Fig 4)**	**Account Item**	**Estimate for Little Swanport Catchment**	**Notes**
			(413)		
x	**N**	**105**	**IMPORT and EXPORT** Water vapour	**4100 GL**	Not considered in water balance (net balance effect is zero). Largely independent of rainfall. Calculated as 880sq km * 4.7GL/sq km (S4)
			IMPORT and EXPORT Inflows and outflows from the sea to surface water		
		106	Tidal flows	**119 GL**	325ML per day in and out - net = 0
			Desalination	**0 GL**	
		107	**IMPORT and EXPORT** Groundwater cross-catchment flows	**?**	
		108	**EXPORT** Surface water (watercourse) to sea	**113 GL** (Alternative: 93.6 GL)	• 113GL (S7) Mouth of LS River Source => a minimum figure; gauge is upstream about 5km from river outlet (LS and Ravensdale) into LS estuary; annual flows ranged from 12GL to 190GL ; mean annual is 113; based on 1971-1990. • 93.6GL (S1) • Seasonal flows are highly variable but winter flows are generally higher than summer; monthly flows also highly variable * note limited flow data in LS only 19 years; did modelling to assess
			Unaccounted for rainfall loss	**0 GL**	Zero because calculated from runoff, evap, transpiration, deep drainage %s of rainfall (S3)

Added to SKM - AWR (2005) model	***Nature (N) or Human (H) Influence***	**LS Code (see Fig 4)**	**Account Item**	**Estimate for Little Swanport Catchment**	**Notes**
			2. INFLOWS TO SURFACE WATER		
	N		*Rainfall to surface water runoff*		Amount of runoff to surface water depends on many factors including land use, slope, storages and rainfall intensity, depth, spatial and temporal distribution
x	***N & H***	**201**	Surface runoff flows into watercourses	**119.21 GL** i.e. approx 24% of rainfall (existing research estimates of runoff from rainfall vary from 7 to 45%l)	Calculated as: 113GL current outflow + 4.65GL net human use withdrawal + 6GL watercourse loss to GW - 4.5GL GW discharge + 60ML watercourse evap = 119.21GL * Border Riv-G (2008) says 10% runoff * 7 - 10% runoff estimated for most land uses in Macquarie water cycle report AWR 2005 * 45% runoff for Tasmania in BRS
	N	**202**	*Discharge from groundwater to surface water (baseflow)*	**6 GL**	Calculated from net deep drainage = 18GL or 3.5% of total rainfall (S2) with GW to SW baseflow being 25% of level of GW recharge from rainfall (S3).
x	***H***	**203**	Surface water into dams	**4.921 GL**	Includes farm dams and relevant licence dams (latter is only 191ML) 3330 irrigation + 1430 stock and domestic - 30ML to domestic HH + 191stock and domestic for licensed = 4.92 GL
x	***H***		Licence extractions to	**191 ML**	Is all for stock and domestic (S1)

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			dams		
x	*H*	106	Inflows from sea - tidal flush	**119 GL**	
	H		***Returns from economy inside entity (total of urban and irrigation where listed separately)***		
	H		*Urban treated effluent*	**0 ML**	
			Water applied to irrigation and stock and domestic use	**3.469 GL**	Calculated as total surface water into dams (203) 4921 ML - 960 ML dam ET (calculated) - 492 ML GW seepage from dams (10% of diversions) = 3469 ML
	H	204	*Irrigation returns* (to watercourse)	**347 ML**	10% of applied irrigation and stock and domestic water (204) (3.469 GL) returned to SW (estimate only)
	H		*Surface inflow from other entities*	**0 ML**	
	H		*Desalination*	**0 ML**	
	H		*Returns from the economy outside of catchment*	**0 ML**	
			Unaccounted for inflow (error item)		
			Total inflow to surface water		
			3. INFLOWS TO GROUND WATER		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			Natural (predominantly)		
	N		*Recharge to groundwater (excluding irrigation) -* surface water recharge to GW	**24GL**	Calculated from net deep drainage = 18GL or 3.5% of total rainfall (S2) with GW to SW baseflow being 25% of level of GW recharge from rainfall (S3). Deep drainage 3.75% of rainfall (S5)
x	*N*	**301**	Non-watercourse recharge to GW	**19.2GL**	Based on assumption that 80% of SW to GW seepage is not from watercourses
x	*N*	**302**	Watercourse recharge to GW *(Seepage from streams to groundwater)*	**4.8 GL**	20% of SW to GW seepage from watercourses
	N	**107**	*Inflow from aquifers outside of catchment (small - assume zero)*(Groundwater import)	**?**	
			Agriculture/Irrigation		
	H	**303**	*Drainage to groundwater from irrigation*	**693 ML**	Includes stock and domestic to GW. Assumed 20% of applied water for irrigation and stock and domestic use (205)(3469 ML)
	H & N	**304**	Dams - seepage to GW Part of *(seepage from surface water features (e.g. dams, wetlands, etc*	**492 ML**	Estimate only. No data on seepage from dams available; other surface water losses to GW covered elsewhere. Loss calculated as 10% of total water inflows to dams (4.921 GL)
	H		*Conveyance losses (seepage from channels)*		Included in 304?
			Other human		
	H		*Seepage from septic tanks*		
	H	**305**	Groundwater inflow from household	**16ML**	Assumed as 20% of total water consumed (80 ML) and discharged on-site
	H		*Aquifer reinjection (e.g. ASR)*		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			Unaccounted for inflow (error item)		
			Total inflow to groundwater		
x			**INTRA-SYSTEM NODAL SURFACE WATER FLOWS**		* 65% of Little Swanport outflow at Lower Reach (Swanston). Table 1 p9 (S7)
			4. OUTFLOWS FROM SURFACE WATER		
			Nature		
	N	**401**	**EXPORT** *Evaporation from open water and wetlands (excluding major storages and minor catchment dams)*	**?**	
x	*N*	**402**	**EXPORT** Evaporation from watercourses	**60 ML**	Surface area = 100ha x 10000 sq m x 600mm evap/yr
		302	*Seepage from streams to groundwater*	**4.8 GL**	Equivalent inflow to GW; 20% of SW to GW seepage from watercourses (S2, S3)
	N & H	**108**	**EXPORT** Surface water (watercourse) to sea	**113 GL**	See end of this section
	H		***Extraction to the Economy inside catchment***		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
	H		*Urban Diversions*		
x	*H*		Centralised DIST/MAINS	**0ML**	
	H		Household, industry use etc	**NIL**	
x	*H*				
	H		***1. Households***		
x	*H*	**403**	Households - rainwater harvesting, stormwater	**26 - 74 ML**	* Population = 521 estimate from 2006 Census (July); 750 (LSCC 2002); additional 150-200 in Pontypool and Saltworks during holiday period) * 26 ML based on 140L/day ; 74 based on 390L/day Tasmanian average but would be less due to non-reticulated conservation * Dunlop 2000 69kL per person per year = 190 L/day / person
	H		Households - direct surface water extraction	**0ML**	
x	*H*	**404**	Household use from dams	**30ML**	Catchment household water use from other sources estimated at 37-50 ML per year. Use from dams assumed as similar additional total quantity.
			Total household extraction	**80 ML**	Estimated as 30 ML from stock and domestic dams (404) + approximately 50 ML rainwater harvesting (403)
		306	Flows to groundwater from household	**16 ML**	Assumed as 20% of total household water extraction (80ML) and discharged on-site
		405	Household release to evaporation	**64 ML**	Assumed as 80% of total household water extraction (80ML) and discharged on-site

Added to SKM - AWR (2005) model	***Nature (N) or Human (H) Influence***	**LS Code (see Fig 4)**	**Account Item**	**Estimate for Little Swanport Catchment**	**Notes**
	H		***2. Irrigation diversions* (crop, pasture)**		
x	*H*	**406**	Inflows to dams for irrigation - total	**3330 ML**	
x	*H*		Inflows to farm dams (unlicensed) for irrig	**3330 ML**	Calculated from farm dam number x size analysis data (S1)
x	*H*		Inflows to licenced dams to irrig	**0 ML**	No licence irrigation other than Hobbs Lagoon (not fed by LS catchment) (S1)
x	*H*	**407**	Watercourse direct to irrigation	**0 ML**	
x	*H*		Total surface water to irrigation	**3330 ML**	
x	*H*		Losses		
x	*H*	**408**	Irrigation to evapotranspiration and other losses excluding return to GW	**2429 ML**	Includes losses from stock and domestic (411). Calculated as the balance of total water diverted for these purposes (408) minus dam losses and GW and surface water returns from irrigation and S&D. Part of 104.
x	*H*	**304**	Irrigation water return to GW	**693 ML**	Includes losses from stock and domestic (412). Assumed 20% of water applied for irrigation and stock and domestic use
x	*H*		***3. Stock and domestic diversions***		
x	*H*		Farm dams (unlicensed) to stock and domestic	**1428ML**	S1
x	*H*		Licensed dams to stock and domestic	**191ML**	S1
x	*H*	**409**	Total dams to stock and	**1619ML**	

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			domestic		
x	*H*	410	Watercourse direct to stock and domestic	0ML	Excludes rainwater harvesting. Unknown for stock.
x	*H*		Total surface water to stock and domestic	1618ML	
x	*H*		Losses		
x	*H*	411	Stock and domestic to evapotranspiration and other losses excluding return to GW	2429 ML	Includes losses from stock and domestic (408). Calculated as the balance of total water diverted for these purposes (408) minus dam losses and GW and surface water returns from irrigation and S&D. Part of 104.
x	*H*	412	Stock and domestic water return to GW	693 ML	Includes losses from stock and domestic (304). Assumed 20% of water applied for irrigation and stock and domestic use
	H		*Urban stormwater*		Covered in household above
	H		*Minor catchment dams*		Covered in irrigation and stock and domestic use above; household above
	H		*Private diversions (on site residential greywater re-use)*		
	H		*Rainwater tanks*		Covered in household inflow from surface water (401)
	H		*Environmental extractions (consumed within Basin)*		
			System losses - storages		
	H		*Evaporation from major storages*		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
x	*H*	413	Evaporation from all dams	**1000 ML**	Includes farm dam surface area + Hobbs Lagoon and other licences
x	*H*		Evaporation from farm dams - unlicensed	**960 ML**	1.6m sq m surface x 1000litres x 0.6m/yr evap (Derived from S1)
x	*H*		Evaporation from entitlement, licence dams	**40 ML**	Estimated in ratio of licence dam storage water use to farm dam storage (4%)
	H		*Losses from infrastructure / operational losses*		
	H		*Evaporation from channels*		Included with assumed irrgtn losses
	H		*Losses from minor catchment dams*		Included with evap losses from all dams above
	H		*Conveyance losses (seepage from channels)*		
	H & N	305	*Seepage from Surface water features (e.g. dams, wetlands, etc) and other losses* to groundwater (Dams here only)	**492 ML**	Estimate only. No data on seepage from dams available; other surface water losses to GW covered elsewhere. Loss calculated as 10% of total water inflows to dams (4.921 GL)
	H		*Flood plain harvesting*		
	H		*Treated effluent discharges*	**0 GL**	
	H		*Urban diversions*	**0 GL**	
	H		*Irrigation diversions (toSWMA)*		
	H		*Unregulated flow (floods)*		
	H		*Releases from dams to satisfy environmental commitments downstream of entity*	**0 GL**	
	H		*Rainfall / runoff harvesting*		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
	H		*Transfers to other entities*	**0 GL**	
			Other flow out of entity		
x		**106**	**IMPORT and EXPORT** Tidal inflows and outflows to sea	**119 GL**	325ML per day in and out - net = 0 ; Source: Objective 1
			Aquifer reinjection (e.g. ASR)		
			Unaccounted for outflow (error item)		
			Total outflow from surface water		
55	**H & N**	**108**	**EXPORT** Total watercourse outflows at catchment (system) boundary	**113 GL**	See previous descriptions in Section 1.
			5. OUTFLOWS FROM GROUND WATER		There is little use of groundwater in Tasmania and no information on groundwater in catchment.
			Nature		
	N	**202**	*Discharge from groundwater to surface water (baseflow)*	**6 GL**	Calculated from net deep drainage = 18GL or 3.5% of total rainfall (S2) with GW to SW baseflow being 25% of level of GW recharge from rainfall (S3). Important during periods of low flow.
	N		*Groundwater discharge to springs*		
	N		*Groundwater discharge to ET (does not include unsaturated zone usage by vegetation)*		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			Extraction to the economy inside entity		
	H		*Urban Diversions*		
	H		*Irrigation diversions*		Irrigation and stock and domestic use accounts as for irrigation but no data available - groundwater use is minimal in LS Catchment
	H		*Groundwater extractions*		
		501	Groundwater to irrigation	**200 - 300 ML**	Not included in farm water use calculations above. S10 p10 ; 197ML estimate from *Water Use on Australian Farms 2005-6*; 220ML as 22% of area of Southern Stat Div (S4) Assumed as mainly irrigation.
x	***H***	**502**	Groundwater to dams	**0 ML**	Relatively small volumes (S8)
	H		*Petroleum wells*		
	H		*Extraction for Aquifer reinjection (e.g. ASR)*		
	N		*Inter-aquifer outflow*		
	N	**107+D54**	*Aquifer flow out of catchment* - groundwater outflow from system boundary	**?**	
	H		*Extraction to economy outside catchment*	**0**	
			Unaccounted for outflow		
			Total groundwater outflows		
			6. USE OF WATER (by SUPPLY and RELEASE)		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
	H		**AGRICULTURE**		
			Supply		
			Surface water diversions to dams - for irrigation	**3330 ML**	All from farm dams (non-licensed)
			Surface water diversions to dams - for stock and domestic	**1400 ML**	1430 ML ; 30 ML to domestic household use
			Groundwater - dams	**0 ML**	
			Surface water - direct	**0 ML**	
			Other supply sources	**0 ML**	Would include mains and from other industry in more detailed analysis and diverse economy
			Release		
			Evaporation from dams (farm dams)	**960 ML**	
			Seepage from dams	**492 ML**	Estimate only. No data on seepage from dams available; other surface water losses to GW covered elsewhere. Loss calculated as 10% of total water inflows to dams (6.4GL)
			Returns to watercourse	**347 ML**	From irrigation
	H		**HOUSEHOLD**		
			Supply		
			Main reticulation	**0 ML**	
			Surface water - dams - domestic	**30 ML**	
			Groundwater - dams		
			Surface water - direct		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			Rainwater harvesting	**50 ML** (26 - 74 ML)	See Surface Water outflow entry above (though is stored as surface water within system)
			Other supply sources		
			Total household water use	**80 ML**	Assumed as 30 dam water use + 50ML rainwater harvesting use
			Release		
			Evaporation of water/wastewater discharge from household	**64 ML**	Assumed as 80% of total water consumed and discharged on-site
			Return to groundwater	**16 ML**	Assumed as 20% of total water consumed and discharged on-site
			Returns to watercourse	**0 ML**	
	H		**FORESTRY**		No additional extracted or diverted water used for production forestry or plantations in Little Swanport. Source: Chris Beadle, CSIRO
	H		**OTHER INDUSTRY**		
x		**601**	Oyster farm flows		Complex fresh and saltwater supply and use patterns for oyster and fish farms
			7. CLOSING STORAGE BALANCE		
			Closing balance - water in store		
	H & N		Major on-river reservoirs		
	H		On-stream minor and farm dams (unknown, record as zero - assume same at start		

Added to SKM - AWR (2005) model	*Nature (N) or Human (H) Influence*	LS Code (see Fig 4)	Account Item	Estimate for Little Swanport Catchment	Notes
			and end of period)		
	H		Major off-river storages		
	H		Off stream minor and farm dams (assume zero as accounted for under catchment farm dam diversions)		
	N		Renewable non-saline aquifers		
	N		Renewable non-saline groundwater outside GMUs		
	N		Renewable saline aquifers & groundwater (neglect - not part of water resource)		
	N		Non-renewable aquifers and groundwater (capable of being mined)		
	N		Soil - unsaturated zone (assume no change - hence ignore)		
	N		Snowpack (no snow)		
	N		River channels (record as zero - assume same at start and end of year)		
			Unaccounted for storage (error item)		
			Total closing balance		

Surface (fresh) water outflows are estimated, depending on the source adopted, as between 93 ML and 113 GL per annum. While 113 GL is noted by the DPIWE (2003) as the estimated mean annual total catchment yield at the mouth of the Little Swanport, it must be remembered that this estimate is based on flow records between 1971 and 1990 and rainfall in the catchment has decreased substantially since this period (2002-3). This account item is a central one given the interest in the levels of economic extraction and use of water from the system, and potential water quality implications for the Little Swanport Estuary. The 113 GL surface water outflow estimate is adopted throughout most of the following analysis.

Most sections of the water account begin with indicators that are primarily "nature" based flows and finish with those linked more closely to economic activities. In section 2, the major sources of inflows to surface water are outlined. The level of runoff from precipitation is meant to represent water that enters major watercourses at some stage in the catchment. It has been calculated as 119.2 GL by adding, to the 113 GL outflow in the estuary, 4.65 GL of net human extractions, a 1.5 GL net loss to groundwater from waterways, and 60 ML of water that would have been lost from the watercourse surfaces. The discharge from groundwater to surface water (base flow) is estimated as 6 GL from ratios indentified in other Australian settings.

The surface water to dam flow levels are important and represent the major part of the human diversions of water for agriculture in the catchment. 4.92 GL is calculated from the 2002-3 farm dam analysis by SKM (2004) and is comprised of 4.75 ML from non-licensed farm dams and 191 ML from licensed sources. When the additional estimate of approximately 80 ML of water abstracted by households is added to this flow into dams we obtain total diversions of surface water of close to 5 GL. In terms of the net impact on likely watercourse flows, we have to deduct the 347 ML that might return from irrigation. Hence, the overall economic extraction from surface water flows out of the system would be 4.653 GL. Note that water use from dams is not based on farm dam size (which obviously has no direct relation to annual consumption) but has been calculated by SKM via survey-based experience with usage rates based on water use type. The actual water applied to irrigation and stock and domestic water has been estimated as total surface water flows into dams (4.92 GL) minus dam evaporation (960 ML) and groundwater seepage (492 ML). Evapotranspiration and groundwater seepage from applied water is calculated by a ratio to this quantity.

In section 3 of the water accounts, estimates of inflows to groundwater are presented. As discussed, there is a paucity of groundwater information in this part of Tasmania (and Australia in general). Hence, the estimates are meant to be indicative only and open to revision once thorough groundwater investigations are undertaken. The 24 GL recharge from precipitation has been used in the overall simple annual water cycle equation above. The major sources of groundwater inflows from humans would come from irrigation water and dams (estimated as 693 ML and 492 ML per year respectively). The remaining discussion focuses upon human intervention and competition and trade-off between economic uses in Little Swanport catchment. The competition, if there is any of significance, is between upland catchment farming and existing oyster production. Section 5 (the outflows from groundwater) has two accounting item entries – the discharge from groundwater to surface water (6 GL) and an inflow for surface water with a speculative estimate of 200-300 ML of groundwater extracted for farm water use. This groundwater is modelled in the accounts.

The outflows from surface water have the most detailed section in the account given better information and the clear relevance of this. Three major "natural" losses from surface water are losses to the overall system – evaporation from open water and wetlands, and watercourses (the latter calculated as 60 ML) and, of course, the large volume of outflow from surface watercourses to the estuarine and oceanic system boundary (previously identified, for our analysis as 113 GL per year).

There are no "distributed" or mains water flows in the study area as we get in cities and towns in modern times. The self-extracted volumes to the economy have been split into irrigation and stock and domestic components, though evaporation and seepages losses to groundwater are combined for dam irrigation and stock and domestic use once the water has been taken from the storages. Losses from dam storages (960 ML per year for non-licensed dams) are presented separately after these estimates.

Human impacts on the Little Swanport water cycle

Detail for the economic side of environmental – economic resource accounts has many potential applications. In our Little Swanport catchment, there are at least two direct purposes. Firstly, we need to gauge the overall extent of human intervention and demands upon the catchment's water cycle. This gives an idea of the extent to which the "natural" flux of water is disrupted by human activities. Secondly, data about water use for different economic and household purposes (and their sources, and releases or losses) are vital for assessing competing demands, and to evaluate management options that will be the best for society overall. In view of a concern with impacts of terrestrial catchment activities on those in the estuarine region, a particular interest is to understand and measure the human impacts on surface water outflows in terms of interrelated water quantity and quality. The water demands for each major economic sector are presented and explained briefly below. This is flowed by the summary and description of the most significant surface water interventions. Groundwater use is not considered in the following discussion.

Apart from agriculture, water use by **other industry** in the catchment is minimal and is unlikely to have a significant impact on surface water flows. This is because there is no significant industry in the catchment. There is also minimal supplementary application of water for the 11.7 % of the catchment under **plantation and production forestry**. This economic use is relevant to the water cycle but probably more in terms of its impact on runoff and evapotranspiration effects (reducing runoff and immediate surface water flows). If plantation forestry continues to replaces cleared land, it could become an important factor for change in the area.

Household water use has been based on an estimated permanent population of 521 people. There are no reliable statistics on per residential water consumption per person. Proxies range from 140 litres per day for consumption in other drought-afflicted regions of Australia (notable South-East Queensland) through to 390 litres per day (the Tasmanian average in 2006) and 197 litres per day for the Southern Statistical Division (Dunlop 2003). Hence, using the population figure, we get a range from 37 to 84 ML per year for residential use. 50 ML has been selected on, dominantly rainwater harvesting. However, given the rural or semi-rural nature of much of the residential population an additional 30 ML has been allocated from the "stock and domestic" extractions in farm dams. Overall, residential water use is therefore estimated at 80 ML per annum. As expected, **agricultural water use** takes the lion's share of human water use prior to estuary surface water outflows. Two main approaches have been used to assess water extractions and demand by farmers.

Firstly, water use has been estimated on the basis of the number of dams of different sizes identified in the catchment. The primary source of these data is the SKM (2004) report which uses the TEDI model and the frequency distribution of identified farm dams by size. The estimation procedure is quite complex and involves conversion of surface areas to volumes, and a mix of assumptions and evidence about the relations between type of use and annual capacity use, and dam size use type relations. The SKM data has been used to split the total farm dam water use of 4.76 GL into irrigation (3.33 GL) and stock and domestic component (1.43 GL). As discussed 30 ML of the latter withdrawal has been allocated to domestic or residential use. Based on a sub-catchment 2002-3 current use survey, an additional 191 ML from licensed allocations has been added to the stock and domestic use levels. Water entitlement information is of limited use to the study given it does not involve actual use and the vast majority of these allocations refer to Hobbs Lagoon which is fed by water from outside the catchment. Hence, according to this farm dam based method, overall agricultural water withdrawals from surface water were approximately 4.921 GL (in 2002-3).

A second approach to estimating agricultural water use is to identify the number of livestock, and quantity of agricultural output (or land-use equivalents), and attempt to apply appropriate water use ratios to these levels. Estimates based on water demand for the estimated stock number yield quite similar results. Based on 150 000 sheep in a typical year and drinking, service and water loss levels of around seven litres per day each, (DPIWE 2003 and Marwick 2002), direct stock needs can be calculated as :

1 150 ML = 150 000 sheep x 21 litres/day x 365 days

If 1.15 GL is added to the 3.3 GL estimated for irrigation purposes, we obtain around 4.5 GL of agricultural water use – close to the outcome based on farm dam statistics. It is important to note that later on, where the very same drought of the later part of the first decade of the 21st Century is taken into account, the data used in the model here is replaced with information based on drought conditions. In other studies of catchments we would be unlikely to be concerned with severe drought conditions as this one. We would be willing to accept long-run averages. The recent drought in the southern midlands of Tasmania is a record.

In this alternative approach, there would be other uses of surface water that would add to this estimate. For example, there is potato growing and other horticultural although limited. The only available research suggests that the use of extracted water (from catchment flows) for cropping is minimal. Our research did not turn up evidence of significant use of water for crops.

Water use and requirements for **aquaculture activities** in the Little Swanport estuary are very complex and difficult to link to catchment water accounts. The water accounts are useful in establishing and measuring the natural and human factors influencing surface water outflows and hence the water quality conditions affecting economic activity in the estuary. However, major informational shortcomings arise in terms of (1) the relationship between changes in water quality and economic output for oyster production, and, (2) in clearly identifying the extent and interaction of freshwater and seawater flows and resulting water quality conditions in the estuary.

Table 8 presents the main water account data relevant for assessing economic surface water impacts prior to the estuary outflows. It covers agricultural and household-related flows only (and the latter component is relatively insignificant). The items have all been introduced and described previously and have been compiled into this table to facilitate the assessment of the likely overall human impact on surface water outflows and potential estuarine water quality and quantity.

The table shows that around 4.9 GL of surface water is extracted for agricultural purposes. Most of this is captured as non-major watercourse flows from farm properties into dams. The ongoing flows linked to this extraction are depicted by the arrows in the table. Evaporation and seepage losses from the dams reduce this quantity to around 3.5 GL which is actually applied for irrigation and stock. In turn, most of this water is lost as evapotranspiration (2.4 GL) and losses to groundwater (693ML) with 347 ML) estimated as returns to surface water. If we add approximately 80 ML extraction to households, there is a total economic extraction of around 5 GL of surface water in the study area. The evapotranspiration losses (totalling 3.45 GL) are definitely a loss from the catchment system boundary and, effectively, the groundwater losses (totalling 1201 ML) can be considered not to provide new sources of supply into available surface water (though additional research could throw new light on this aspect). The estimated surface water returns from irrigation (347 ML) are deducted from the total extractions to generate an estimate of **4,653 ML of surface water net extractions from the Little Swanport catchment.**

If the net extractions are added to the "post-economy" surface water outflows to the estuary, we can estimate the total "natural" outflows into the estuary at 117.65 GL per annum (= 113 + 4.653 GL). Hence, **the economic extractions lead to a 3.95% reduction in surface water outflows that would occur without humans**. Returns to the catchment from irrigation from Hobbs Lagoon (with its water extracted from outside the catchment) have not been included in the analysis as there is some debate as to how much water is actually transferred from Hobbs Lagoon to the LSP Catchment. As discussed, the actual water cycle outcomes that would be observed without humans are very difficult to identify especially in view of the extensive land use modifications (affecting runoff, groundwater seepage, evapotranspiration and water quality) that have only been partly accounted for in these calculations. If the 93.6 GL figure for existing annual outflow is utilised (as per the SKM (2004) analysis), the reduction increases to 4.7%. If we use the stock water use levels based on number of sheep by water needs (1.15 GL versus 1.4 GL), the reductions are 4.7% and 4.5% for the 113 GL and 98.6 GL outflow levels respectively.

Table 8 Overall Extraction and Losses by Economic Sector

Sector	Surface Water - Volume Extracted	Losses from Evaporation and Transpiration	Losses to Groundwater	Returns to Surface Water
Irrigation	**3330 ML** (Hobbs Lagoon)	**2 429 ML**	**693 ML**	**347 ML**
Stock and domestic	**1 400 ML** (1430 – 30 ML to households) + **191** (licensed source extraction)		subtract	
	TOTAL Irrigation and Stock = **4 921** ML			TOTAL water applied to irrigation and stock = **3 469 ML**
Dams	Covered in irrigation and stock and domestic above	subtract **960 ML**	**492 ML**	-
Household	**30** ML (from dams) **50** ML (rainwater harvesting) TOTAL = **80 ML**	**64 ML**	**16 ML**	
TOTAL	**5 000 ML**			

TOTAL FLOWS DIVERTED BY DAMS (excluding households) =
4 921 ML = 3330 (irrigation) + 1400 (stock ; non-licensed) + 191 (stock ; licensed)
TOTAL WATER APPLIED FOR IRRIGATION AND STOCK =
3 469 ML = 4921 (dam diverted flows) – 960 ML (dam evap) – 492 (dam seepage)
FATE OF WATER APPLIED FOR IRRIGATION AND STOCK = 3 469 ML
347 ML to surface water (10%) 693 ML to groundwater (20%) 2 429 ML evapotranspiration (balance)
TOTAL SURFACE WATER DIVERSION =
5 000 ML = 4 921 (Dam diverted) + 80 ML (Household)
RETURNS TO SURFACE WATER FROM THE ECONOMY =
347 ML (Irrigation and stock to groundwater)
NET CONSUMPTION OF SURFACE WATER (including losses to groundwater) =
4 653 ML = 5 000 ML – 347 ML (3 452 if loss to groundwater not considered consumption)

The value of water

Tor Hundloe

Our catchment is different to those that supply towns and cities with water for residential purposes, and those that supply industry (such as cooling for power plants). It is a simple catchment, meeting simple needs – farming, oyster growing, and residential needs for drinking and washing water. We have already explained the conflict which has arisen over the proposal to change water allocation in the catchment. Rather than to go immediately to the issue of the value of water (if switched) between users, we take the effort to explain practical human-weather interactions.

We start with farming. Most farming in the developed countries is a business, yet in many important regards it is different from other businesses. The vagaries of nature do not have to be dealt with by most industries, while droughts and floods have fundamental influences, both desirable and undesirable, on farming. Most disasters that affect the supply of farm products are natural ones. They can occur quickly – a flood, a cyclone – or take a little more time to have an impact as a drought does. The vagaries of markets, a change in consumer attitude that puts fax-machine manufacturers out of business are gradual and change can be planned. Industries other than farming (manufacturing and the service industries) are, in general, protected from changes in the natural world.

Extreme weather events are unlikely to effect the production and supply of white-goods, motor vehicles, or oil production, to name three common commodities. Factory operators do not have to build into their day-to-day, season-to-season, or year-to-year planning, the probability of a major loss of production due to floods or droughts. On the other hand, farmers must expect droughts and floods. The idea of one bad year in seven is the conventional wisdom imbued in children growing up on farms everywhere in the world.

The extent to which farmers build extreme weather events into their expectations of the future is a key determinant of the profit, or loss, they are likely to make. Expect next year to be as good as the last year – when last year had optimum rainfall in the growing season – and financial disaster awaits. The converse holds true. The eternal pessimist will believe the drought will never break and won't be ready for the much needed restocking and replanting when the rain comes.

Obviously, the wise farmer considers the long-term future in his or her planning. In looking to the future, there is limited value in looking to the immediate past. The longer the period over which averages are calculated, the more likely it is that a "true" average will be estimated. Even with long term averages, the future will be unknowable. We are always dealing with expected outcomes and expected values, not actual (knowable) ones. What we expect is based on our past experiences, the past experiences of those we converse with, the things we have read, and any other valued influences. Because of this, expectations are not subjective; rather they are, in part, objective, based on experience and reasoned thinking. The more information we bring to bear, the more objective our expected future.

We can – and should – assign probabilities to future events. A probability, such as a one-in-ten-year flood, is based on good science. The less we know about the matters that influence a possible event, or the poorer our records of historical events, the less firm our assigned probability of a future event. We had been improving our predictive ability with regard to the climate. All that good science is now being reworked and rethought as we attempt to come to grips with climate change. Climate change has added a great degree of uncertainty with regard to the likelihood of extreme events. The better our knowledge of what "drives" weather systems, the more accurate will be our assigned probabilities. However it is not just the prospect of climate change that is making the task of forecasting the future extremely difficult. There are three major influences at play in the early 21st century; the prospect of significant climate change; the rapidly changing Asian economy; and the threat of global over-population. All are decreasing our predictive capability because they are inter-related which makes the forecaster's task more difficult.

Let us not place all emphasis on nature as the compounding variable. The market (supply and demand) is subject to another set of vagaries. These are beyond the control of farmers as a group and certainly are beyond the control of an individual farmer. Significant shifts in exchange rates can have a major effect on profits for products sold in a set currency (usually the US dollar). Some currencies – in some periods – tend to fluctuate widely for no apparent rational economic reason, and hence make planning very difficult. Currency speculation is the root cause of the problem. So serious is it that Nobel Laureate economist, James Tobin, has been arguing for a tax on international speculative transactions for decades. Australia would be a major beneficiary of the cessation of currency speculation. Don't hold your breath waiting for it. The speculators are more politically powerful than that of the economic reformers. The volatility of the Australian dollar over the past 20 years – notwithstanding the country's long-standing robust economy and political maturity – is impossible to explain on rational grounds. In the late 1980's the Australian dollar approached US 90 cents, it fell back to hit a low around US 50 cents a few years ago, to reach over US 95 cents in late 2008 and drop back to 65 cents in early 2009. The dramatic changes can only be explained by the action of speculators. The so-called economic fundamentals (that is, real world variables) do not change as fast and as dramatically as these fluctuations. Australia can be a business-person or traveller's nightmare, and the asserted benefits of a floating exchange rate warrant serious questioning.

There are other difficulties facing a firm in planning for the future. Consumer tastes change, a classical example of this relevant to our case study is the substitution of synthetic fibres for wool. This became obvious in the 1970s and contributed to the reduced demand for woollen fabrics. This could be about to turn around with the dramatic increase in price for the major source for synthetic fibres, fossil fuels. Even if their prices ease in the future, the long term prospect – as we approach what is called "peak oil" – must favour wool and the other natural fibres.

The fluctuations in wool prices, production and exports have been one of the most dynamic features of the Australian economy over the entire history of the nation. A little more than over 100 years ago Australia was one of the richest countries of the world because of the strong demand and high price paid for fine wool by the UK clothing industries (and elsewhere, for example, Italy). The demand for the very good quality Australian merino wool remained buoyant throughout most of the 20th century. During the Second World War massive stockpiles of wool were contained in specially built wool stores. After the war exports became possible again. Not long after, during the Korean War (1950-1953) Australian wool sold for "a pound a pound". Do not worry about making the conversions; it was an excellent price, the highest ever. Australia "rode on the sheep's back" until 1970. Since then prices have fluctuated widely, so have sheep numbers, and consequently wool production. Changing the level of production in line with price changes is rational. If the price of beef increases while that of wool decreases, the farmer who can convert to beef production will. Sheep numbers will decrease, those of beef cattle increase. The facts are recorded in official statistics. Not all farmers can make the obvious, sensible change, due to the nature of their land or lack of finance – if sheep become of little value how do you make enough money by selling them to purchase cattle? Being a "first mover", anticipating change and responding to it before others, can make all the difference between profits and financial ruin.

Farmers tend to rely on one product, or at the best very few products (say wool and fat lambs, or bananas and pawpaws), and are not able to spread their earning opportunities (and risks) like other businesses where a decline in demand for one item is compensated by an increase in demand for another. Think of the average supermarket. It does not matter that canned soups go out of fashion. Customers will be purchasing a substitute from the same shop. A wool property cannot produce a petroleum-based fibre. It is with this background in mind that we can start to understand businesses, and farming in particular, in the Little Swanport catchment.

Our case study

When we had gathered as much data as possible from farmers in the Little Swanport catchment and searched among it for the relationships between income and water use we were expecting, the results simply did not appear. There were no statistically valid relationships. Farm profitability showed no pattern according to water use. There were two problems.

They were not necessarily unexpected, but as with most empirical investigations in science, the researcher commences by using the conventional, and least costly research tool even though the investigator knows from the start that the tool might not show up a useful result. It is, then, on to the next (usually more costly) research method, and so forth until reliable results are uncovered or the investigation is discontinued. Most science is like this. Much of it leads to a dead end, something the lay person does not necessarily appreciate as (like the lottery) only winners make the news. Come the dead end, someone tries something new.

What were the problems we faced with the Little Swanport investigation? First, there simply were not a sufficient number of farms with similar characteristics to allow for the construction of a representative production function. There are a relatively small number of farms in the catchment – of the total population of 521 people many are not farmers, and the average farm has a number of household members. Then there is great variability in farm size and type of farming. There was nothing we could do about this except hope that a large number (the majority) had similar water-use demands and earned similar levels of income. As stated, this proved not to be the case. We did discover how many water holes a farmer had (there are approximately 1,200 in the basin) and how much pumping equipment was employed. Furthermore, we obtained information relating to government permission to access water and the fees involved. However none of this helped us develop a reliable production function. A major research road-block to our research had been encountered. Each and every farm had its unique water demands and production functions. It was not going to be possible to model water productivity across the farming community.

Second, most farmers had no comprehensive data on water used. Their animals drank from the large number of man-made water holes or from creeks and rivulets that ran through their properties. It is not possible to measure water consumed in this way. This is in contrast to say, fertilizer applications. All farmers had records of the monetary value of the fertilizers purchased and used, and likewise for a large number of other farm inputs. Water, not being bought and sold in a market, went largely unrecorded. And of course water is not simply consumed via animals drinking it – the grasses, clovers and other feeds are fed by water, in the main by rain. This indirect demand for water – we won't call it virtual water as this term tends to be confined to water extracted or diverted from a natural source – is very noticeable on farms. Country turning brown, and remaining brown season-to-season indicates a lack of rain – a drought. Rainfall data is something farmers gather and work with. The relationship between rainfall and income is measurable. This is what we will use to estimate the value of more, or less, water to the terrestrial farmers.

There are, as they say, many ways to skin a cat and we found one in the variations in rainwater. They provided the link between profitability of farming and water that we were searching for. While this worked for the technical farmers, the value of water (in both quantitative and qualitative terms) for the oyster farmers had to be addressed by a different approach.

The relationship between an environmental state (rain or no rain) and productivity (measured as monetary returns) is called the "damage cost" when the state of the former reduces the latter. Damage cost analyses are one of the many techniques which have been developed over the past 30 years to ascertain economic values for environmental (or natural) resources. These techniques are common to two sub-fields of economics, natural resource economics and environmental economics. Much of the early theoretical and practical work in popularizing these tools was done by a group of practitioners at the East-West Centre at Honolulu, Hawaii. In 1983, their work resulted in the publication titled "Environment, Natural Systems and Development: An Economic Guide' by Hufschmidt et al. Two subsequent publications "Economic

Valuation Techniques for the Environment" edited by John A. Dixon and Maynard M. Hufschmidt (1986), and "The Application of Economic Techniques in Environmental Impact Assessment" edited by David James (1994) contain numerous case studies, each utilizing a different technique. In the latter book, Hundloe uses a "damage cost" approach to analyse a change in farming practices in the upper catchment of the Chao Phraya River which drains much of Thailand. The river flows through the centre of the country and is known as the Chao Phraya River Basin, a fertile alluvial flood plain from which rice is produced and exported to other parts of Asia. The approach used by Hundloe is not dissimilar to what we used to obtain a measure of (increased/decreased) water to Little Swanport catchment farmers. Jeff Ross (Objective 1) estimated the value of water flows to the end-of-the-catchment oyster farmers.

The impact of drought in the Little Swanport catchment

The point of commencement is to seek correlations between rainfall and farm income, and note how farmers respond to changed weather conditions. Droughts are normal – and expected – occurrences in Australia. The concept of a drought is a relative term. A drought in a tropical rainforest area is vastly different to a drought in a semi-arid desert. The small Australian state of Tasmania provides a good illustration of this variability. The World Heritage-listed temperate rainforests of the southwest of Tasmania receive abundant rain – that is why they are called "rainforests". While the east coast, particularly our case-study area, is the driest in the state. A drought in the Little Swanport Catchment area is likely to cause serious problems for farmers who even in the best rainfall years rely on the large number of small farm dams to water their stock.

The effects of an extremely severe drought started to be felt in the catchment in late 2006, early 2007. There were drought conditions leading up to this period, but not as dramatic as they were to become. The previous year, 2005, had seen very good rainfall – more than normal. The severity of the drought varied across the catchment and hence its impact on farmers varied according to their geographic location and the type of country they farmed. Various environmental conditions, the extent of forest cover, soil type, and the duration of rainfall events have an impact on the value of water to a farmer. From the onset of the drought, some farmers overlook a level of "preventative or defensive" expenditure; however the worst impacts were not felt until considerably later, and only then did the costs become high.

Preventative (defensive) expenditure

Where a producer (or consumer) takes action to avoid a cost such as the loss of sheep or cattle in a drought, economists use the term "preventative expenditure". Money that would otherwise not be spent is outlaid to prevent something undesirable happening. A typical example of preventative expenditure is a household installing double-glazed windows if his or her house is in a flight path. The noise is avoided, but at a cost! Drought-affected animals can be saved, but at a cost of fodder purchases.

A loss of farm output is given the simple technical term in economics of "loss of production". Alternatively it is called "foregone production". The loss of farm output is "damage" to the enterprise resulting from unusual environmental conditions. Damage tends to be causal by pollution and degradation of the natural environment, however, the same principle applies to a less then optimal environmental state. Measuring the loss of production is the favoured technique to calculate environmental costs. Its equivalent when workers' productivity declines due to environmentally unhealthy working conditions is given the similar simple description "loss of wages" or "foregone wages". Both types of losses are known by the generic name of "damage costs". Something unwanted happens to the environment (pollution, a flood, a drought) and damage is done to the productive capacity of the business.

The impacts of the severe drought on the Tasmanian East Coast were not felt in the three years covered by our initial survey (2003-04, 2004-05, 2005-06). As a consequence, the farmers did not report spending much to counter the negative effects of the drought. Only by revisiting catchment farmers in late 2007 did we obtain data on the effects of what had by then become severe water shortages for many farmers. All farmers were feeling some degree of distress. The various strategies taken by farms in an attempt to prevent the productivity losses due to water scarcity are appropriately called 'preventative (or defensive) expenditure' in economics.

The data in the following table indicates the action farmers were undertaking in the 2005-06 year. We must emphasize the point, this was expenditure made before the severe effects of the drought were felt. Some farmers undertook more than one strategy. The cost to the farmer included the purchase of materials, plus the opportunity cost of his/her labour. The table makes it clear that even in this lead-up to the more severe drought conditions which were to follow, a sizeable percentage of farms were making preventative expenditure. These were to prove insignificant compared to what was to happen.

Table 9 Preventative Expenditure Leading up to 2006-2007

Action Taken	Percentage of Farmers Undertaking this Strategy	Average Additional Costs for Those Taking Action
1. Purchase more than normal stock feed	57%	The average ***additional*** purchases in 2005-06 were $7,600
2. Grow more than normal stock feed	43%	The average ***additional*** material costs were in the order of $20,000 in 2005-06
3. Clearing-out existing dams, installing water tanks & troughs, improving irrigation, digging new water holes	36%	The average ***additional*** material costs were in the order of $15,000 in 2005-06
Other (eg. Use more fertilizer, open up new paddocks for grazing)	14%	

The data in Table 9 indicates that many farmers were not taking steps to counter the drought – at this stage. This was for a variety of reasons, the most important being the marked differences across the catchment in rainfall and water availability (that is, the lack of water was not evenly felt), the shortage of funds by some farmers, and differences in farmers' attitudes and expectations about future weather conditions.

Even when the extent of the drought became all too obvious it was not experienced universally in the catchment. Not every farmer faced the same dire straits and not every farmer responded in the same fashion. The idea of an average farmer, taking average responses to drought is not a real world concept. Don't expect any individual farm to have lost the same amount of dollars as the average. Only by coincidence will there be "an average" farm. Some will have lost more, maybe much more; some will have lost a little, maybe nothing. However, it is possible to arrive at a range of responses which we can use to draw conclusions based on our interviews with farmers and the financial data we gathered from them. From these responses (in terms of preventative and/or replacement expenditures) we can model the value of changes in water quantity. Before going to the data, it helps to spell out the choices faced by farmers.

A drought-affected farmer is faced with two major choices if the farm business is based on stock: sell-down the stock or purchase feed. In some situations there is a third option and that is to purchase water from others who have water allocations in the same system. This is possible in parts of the extremely large Murray-Darling system, but even there of limited scope, due to the very thin and immature water market. There was no one to purchase water from in the Little Swanport catchment when the drought became so severe that farmers would have entertained the idea had it been possible.

Both of the feasible responses (sell stock or purchase feed) follow from the fact that in drought conditions the stock carrying-capacity of a farm is reduced. Selling stock before they are ready for the market will result in decreased prices and obviously a downturn in farm gross income and profits from that expected. Of course, if a farmer sells a lot of animals due to a drought he or she is likely to experience a one-off increase in farm income in that year (notwithstanding the poor price for the stock). The 2007 drought resulted in stock prices for Little Swanport farms falling on average by more than half (58%) of their normal price. This was a dramatic loss for those who had to sell.

If there is no change in demand, price will fall for one of two reasons. First, there is the excess supply at the going price – a significant number of sheep or cattle come on to the market at the one time at a local sales yard can "unsettle" the local market. Given that the number of animals put on the market in Tasmania (let alone that small part of it which is Little Swanport) is insignificant in terms of the Australian total, we can't blame an "over-supply" for driving stock prices down. The second reason for a low price is the change in the quality of the animal – one affected by drought is not going to be of top quality and will sell for less than the normal price

In the Little Swanport catchment farmers who attempted to retain their total stock holdings, or at least more stock than could be fed in their paddocks, purchased fodder as the drought became worse. For some farmers this meant borrowing money. This was in a period when fodder prices were increasing (due to increased demand elsewhere in Australia) and the costs of borrowing were also increasing (the threat of inflation was recognized in early 2007 and the Reserve Bank commenced an ongoing program of increasing the formal interest rate).

The short term impacts of severe drought can be difficult enough to cope with without meeting the costs of rebuilding the carrying-capacity of the farm to its "normal" state. Pasture has to be regenerated after a drought. If this is not done there will be permanent reduction in stocking rates, and hence farm income. This type of cost is what economists call "replacement cost". In its general form, when a part of an enterprise is destroyed (say a farm bridge in a flood) and it has to be replaced before the enterprise can be as profitable as it normally is, the cost of replacing the damaged object indicates its value to the enterprise. The value of good quality soil to a farmer is the cost of replenishing it with fertilizers once the soil has been degraded by over-grazing or over-use. Replenishing eroded and degraded soil as a result of poor farm practices is probably the best example world-wide of replacement costs. Being in the financial position to re-stock immediately after the drought is a prerequisite for long term profitable farming.

Let us summarize at this stage. We have identified three techniques of measurement to calculate the value of extra units of water to farmers. They are the loss of productivity, preventative expenditure and replacement costs. All these can be calculated using market data – such as the price paid for fertilizers, purchasing feed, and rebuilding soils. Economists would say that farmers (or whoever) "reveal" through buying and selling decisions what the costs (benefits) are. No fancy surrogate or hypothetical markets have been brought into play when applying this technique which has taken from conventional economics. This means we can trust the data rather than be concerned that the biases that can result from less direct methods.

The only other thing those in the situation of our Little Swanport catchment farmers can do is better utilize existing water, say by installing reticulation systems. The possibility of doing this is limited to the extent of water in the farmers' dams. In severe drought conditions this is not a realistic option. Whatever farmers do costs money that many haven't got. Let us consider in more detail their responses to changed environmental conditions. We will come to use one or other of the measurement techniques identified above to answer the question: what is the value of an additional unit of water?

Destocking

If de-stocking merino sheep, the first to be sold are wethers and dry ewes, for the obvious reason that they are not reproducing. They don't rebuild the flock. In the Little Swanport catchment during the 2007 calendar year these two categories of sheep had been reduced to less than half (46%) of the normal carrying capacity. Recall this is an across-the-board reduction with some farmers reducing by much larger percentages while others by small amounts (including those able to maintain their complete flock).

Farmers will attempt to retain as many of the breeding ewes as possible. However, during droughts the condition of these animals declines and lambing percentages can be dramatically reduced. In the Little Swanport catchment, the average lambing rate declined in the 2007 drought from round 90 percent to about 65 percent. The reduction in the lambing rate is a simple measure of the stress on the animals. The average lambing rate calculated over a period of years tends to become the expected lambing rate in farmers' minds. A farmers' planning (including financial decisions) would be made on the basis of an expected lambing rate of 90 percent. Unfortunately there is a tendency to exclude from the estimation of the average lambing rate the marked difference an extreme weather event (such as a drought or flood) will have on the average. When an extreme event occurs, as in the Little Swanport catchment in 2007, the differences between its consequences and the expected "normal" can be a serious loss to the farmer.

The drought-induced, reduced lambing rate meant that instead of 900 lambs for every 1000 ewes, there were only 650 lambs. This is a loss of 250 future wool producers (assuming we are dealing with merinos and not crossbred fat lambs). The loss is the net present value of the year-in, year-out loss of wool production over the wool-producing lifetime of the sheep, plus the sheep's final sales value, plus the lambs not born if the sheep is a ewe. The foregone wool production would equal: the weight of the fleece multiplied by the selling price (based on its micron count) multiplied by the number of years the sheep is shorn, minus the costs of maintaining and shearing the sheep. A number of simple arithmetic sums involved here, but all capable of reasonably accurate answers.

As with sheep, drought conditions affect the number of beef cattle that a property can carry without importing fodder. The 2007 drought resulted in a fairly dramatic reduction in breeding cows. The average herd in the Little Swanport catchment in late 2007 was approaching half of what it was a year previously (at 55%). The calving rate also declined significantly. The same type of calculations as for sheep would be undertaken to measure the loss of beef production.

Feeding stock, re-sowing pasture

Little Swanport farmers who could afford to purchase feed (either through the use of their own funds or by borrowing) did so. Our survey results showed that the extent of feeding varied significantly, depending on what level of stocking a farmer wished to maintain, and on the condition of both pastures and "run country" on the property. Obviously the individual farm data which we were provided with cannot be reported, however, we can relate that the largest properties spent from the time the drought began (in the first half of 2006) to the second half of 2007, a period of approximately 18 months, $0.5 million or more on food. This is an indication of the order of magnitude of the monetary value of farm output on the large farms. One does not spend this amount of money if the potential loss is not comparable. The smaller properties, which are the significant majority, spent about one-tenth of this on fodder during the same period. Spending is not necessarily commensurate with farm size, but rather with the ability of the farmer to source funds. Many farmers with small properties could not access the necessary money to buy feed for their stock.

One of the impacts of prolonged drought is the failure of crops. These include food crops as well as grains or whatever else is destined for the market. For farmers running cattle or sheep, pastures are important. In the expectation – or hope – of the drought breaking, farmers re-sow pasture. This is a costly undertaking at approximately $400 per hectare in our study area at the present time. One hundred hectares of sown pasture would cost $40,000, equal to the total gross farm income of the very small farms.

Some simple sums

We can commence to put a value on water to farmers in our catchment. We will use the loss of productivity approach. We will come to an overall estimate later, but first it will be instructive to illustrate what we are doing by drawing on our survey data to construct hypothetical farms, and the value of units of water to them.

A large property of 3000 hectares would, in a normal year, run 8000 sheep plus 50 beef cattle. This is a hypothetical property in the Little Swanport catchment. Any resemblance to an existing property is purely coincidental. The sheep would produce

240 bales of wool, at 33 fleeces per bale. The average selling price for a bale of wool in 2007 was in the order of $1,700.

The 2007 drought resulted in the sheep numbers being reduced on this property to 4800 sheep and the cattle to zero. This means there is at the time of writing, in the order of 1.6 sheep per hectare due to drought conditions, whereas in a "normal year" the same property would run close to three sheep per hectare if no cattle were grazed. This reduced number of sheep would produce 130 bales. The average fleece decreases in weight as a consequence of the drought. The loss from the wool clip is 110 bales, which is $187,000. This is the gross monetary loss from reduced wool sales. However, there are 3,200 less sheep to shear, mules, muster and generally maintain. The net return per sheep is in the order of $30 (half the selling price of the wool). This means that the loss to this farm would be in the order of half $187,000 per year, being $93,500. This is the very minimum value of the rain that did not fall in the drought years. We will present rainfall data later so that income losses can be compared to decreased rainfall. The above does not include the income earned in the year for the sale of the sheep. Only a small number of the 3,200 sheep would have died in the farmers' paddock; most would have been sold at discounted prices as discussed above. These sales would add to the farmers' income in the year of the sale.

If the cattle were sold the income would also show up in the year of the sale and the loss would be in future years. As both the sheep flock and cattle herd have been reduced the value of the property would be coincidentally reduced. The value of a property is largely determined by its profitability. The two tend to change in tandem. For the hypothetical farm we have been discussing, the value of the water that did not fall in the period can be estimated by the net foregone production which is 3,200 sheep at approximately $30 per sheep per year. This is the minimum loss, as only foregone wool revenue is counted. The cattle are left out of the arithmetic as are losses in future years as the flock is rebuilt.

Another large (hypothetical) property (of 3350 ha) would in a normal year run 11,000 sheep plus 200 beef cattle. You will note this property, although just over ten percent larger than the previous one can run significantly more sheep and cattle. It has more better quality grazing land, more improved pastures, and a farmer more attuned to the business of farming rather than the lifestyle of farming. By the time of the 2007 drought, the sheep numbers had dropped to 8000 and cattle to 150. The number of bales produced went from 360 to 240. The wool clip loss is therefore 120 bales at an average price of $1,700, minus the expenditure saved by running and shearing less sheep (i.e. $204,000 minus $90,000 which results in an $114,000 loss). If most of the 3,000 sheep were sold in that year, there would be the income from the sale in that year. However, in future years the impact of the destocking would be significant. The money from the stock sale would increase farm income only in the year of sale. Destocking is what economists call disinvestment. The value of the farm including its stock will drop in the next year and subsequent years. Again we have neglected the decreased cattle numbers and, most importantly the ongoing loss in future years.

Another hypothetical farm, this one of 1000 hectares would normally run 4500 sheep, with approximately an equal numbers of ewes and wethers/dry ewes. No cattle are run. The stocking rate equals 4.5 sheep per hectare. A total of 200 bales of fine to medium wool are produced, which means on average 22 fleeces per bale. This is a significant difference in the fleece weight compared to our other farms, yet such differences are to be expected - some sheep are larger and carry more wool. One of the values of using hypothetical examples is the ability to show such significant differences based on real world data.

As a consequence of the 2007 drought, a reduction of the flock by 450 results in 4050 sheep. This means that the stocking rate falls to 4 sheep per hectare. The number of bales produced falls to 170, now with 24 fleeces per bale. The average fleece is marginally lighter due to the drought. Viewed in these terms the drought caused the loss of production of 30 bales of wool. There had been a smaller reduction in the previous year (2005-06) while the year 2004-05 had been a normal year. The loss of 30 bales (in this case, at $1,500 per bale) results in a figure of $45,000. There are 450 less sheep to shear, which reduces the farm costs by $13,500. This gives a net loss of $31,500 in 2007. Matters were worse for this (hypothetical) farm than the others we have described as the drought had a serious impact in the previous year which was not the case for the others. This impact has not been calculated. The cumulative costs of long-running droughts lead to a greater loss than the one year loss estimated in our examples. The total value of lost production has to be counted over all the years when losses occur.

The loss of wool production on the farm we have just discussed occurred, notwithstanding an increase of area sown for crops. The crop sowing was an additional cost which would have to be included – even though the crop failed. The crop yield declined a little in 2004-05, and then decline in 2005-06 to a disastrous level, next came the extreme conditions of 2006-07. In this situation there was not only the loss of wool but the additional cost of 20 hectares of wasted crop planting.

We have been discussing farms running both sheep and cattle, and the sheep comprise ewes, wethers and some lambs. The calculations have been made as simple as possible by estimating nothing more than the loss of wool revenue. A more complete analysis is required for the mixed cattle and sheep farms. Cattle require more land per beast than sheep, just as breeding ewes require more food than wethers. There is a standard measure by which to convert those different animals and their nutritional maintenance requirements to an equivalent measure (a measure of equivalence). It is the "dry sheep equivalent" (DSE) which is the maintenance requirement of a 48 kilogram wether for one year. As sheep and cattle have different grazing patterns, and grazing is an ever-changing activity, more precise measures than the DSE are used to determine the energy supplied to animals by a variety of feeds and the expenditure of energy by the animals. However, DSE is the conventional "rule-of-thumb" measure.

The impacts of the drought: in summary

During the drought, farmers found that many of their water holes had completely dried up. There was no water for those who irrigated, and no water to cart to outlying paddocks. As a general response, farmers attempted to keep breeding ewes and breeding cows while sacrificing other animals. With some exceptions, the numbers of breeders have been kept constant. However, the number of wethers and dry ewes has been reduced to under half the normal number. The number of steers and stores has been reduced. The number of lambs weaned has fallen to 89.9 percent of the normal.

A very significant number of farms (over 85 percent) are feeding stock, with a number commencing this in late 2006 as farmers' own food reserves were soon depleted. Crops have failed, and when not absolute failure, grain has been fed to stock at a significant opportunity cost. Potato yields have been reduced. When the drought breaks about one-quarter of pastures will need to be resown as they have become degraded. This is the dynamic of a severe drought.

The most marked costs of the drought have been the loss of productivity in wool growing. Most wool producers have experienced a reduction down to 75 to 85 percent of the normal clip. The foregone income is substantial – ironically greater in 2008 than the same loss of productivity would have been only two or three years ago before wool prices were considerably lower Wool became more valuable hence losses more significant. This reinforces a very basic point. The value of water to a farmer (and to others) is "derived" from the value of what it is used, and if the latter changes due to erogenous factors (displacement by a new product) the value of water in this use changes.

Once again it is opportune to remind the reader of the near impossibility of coming to *one* number as the value of water to a farmer – that value changes as the value of farm production changes. In the case of wool, the increase in value was significant. The other very significant cost to most of these farmers was in planting feed crops for the animals. From the loss of wool production we get the initial, minimal impact of a reduction in water availability – in other words the value of the water that was *not* received is the net value of the foregone wool income - a loss in the order of 20 percent. A property producing 100 bales in a "normal" year would produce 80 bales in 2006/2007. The gross value of this lost production would be $30,000 to $40,000, while the net value would be approximately half of these amounts. Given the increased value of wool in the past year, so there is a corresponding increase in the monetary loss. That is, the bales *not* produced would have been more valuable due to the price increases. Here was a "double whammy" for Little Swanport farmers. Put in other words, assume that the same amount of water had been available to farmers in 2006/2007 as was available in a "normal" year; the value of water is given by the net loss due to the difference. *Here we have the value of water in economic terms to farmers*.

On the basis of the new data we gathered in 2007 we can derive estimates of the net economic costs of the reduced rainfall in the years 2005-2006 and 2006-2007. The estimates are based on the impact on the total farming community in the catchment, recognizing that rainfall – and the response to the lack of it – varied significantly across the catchment. Our estimates do not include the future costs, something which we have drawn attention to. A comprehensive analysis of the damage costs (resulting from less water) would estimate the losses year-in, year-out until normal economic earnings returned.

An extremely important feature of the damage caused by droughts is that it does not happen immediately (that is, in the year of the drought) and the damage is cumulative in as much as one impact, for example poor lambing, results in decreased wool clips and meat sales well into the future. This effect can be mitigated by immediately restocking, which comes at a cost

The costs are based on three different measures used extensively in the environmental economics literature: replacement costs, preventative costs, and lost productivity costs (damage costs). For the year 2005-2006, the total across the catchment loss is estimated at $1,553,000. For 2006-2007, the estimate is $3,355,000. In the next chapter we compare these economic losses to rainfall data. From this we can arrive at an indicative value of a litre of water from the farming community.

Estimating the value of water when it does not rain

We now have considerable data from the catchment farmers on how they have attempted to deal with a very serious drought. The lack of rain over the years 2006 and 2007, continuing into 2008 has caused considerable *damage costs*. These are reflected in three different measures. First is *preventative expenditure*. There is money spent by farmers to prevent – or in the hope/expectation of preventing – loss of income. A classic case of preventative expenditure, and one which has nothing to do with farming, is the sound-proofing of residential, community and commercial buildings under aircraft flight paths, so that noise does not disturb people at work, rest or play. The second measure is *replacement cost*. This is where something that is lost – in our case green grass due to lack of rain – is replaced by the purchase of feed. The cost of bought animal fodder is the value of the water that *had it fallen* would have grown the grass. In the case of the Little Swanport catchment we can realistically combine preventative expenditure and replacement cost as joint damage costs. The third measure is the *loss of production* (such as decreased crops, less animals able to be fed and consequently less wool and meat). The loss of productivity leads to less profits, wages and other returns to farm inputs. The monetary sum of the loss of profit to farmers is the (minimum) value of the water that *did not fall*.

All three measures give us the monetary value of an input (water). The data we have shows the monetary loss starting from a position of normal rainfall and declining, in our case, dramatically. When the drought eventually breaks we could undertake the much more simple exercise of recording the increase in profits that result from the added quantity of water (as rain) which returns the situation to normal. In applying these three measures it is important, as it is in all economic analyses, to avoid double counting. Alone and in total all the three measures reduce profits and it is necessary to ensure the impact of one is treated separately from the impact of others.

We are going to use rainfall, which is conventionally measured in millimetres, rather than water captured, which is conventionally measured in litres, to obtain its value. The use of millimetres is appropriate in our case because what we have in the catchment is rain-fed agriculture with only limited irrigation of crops. While the larger farms are a combination of improved pastures and run-country, and the improved pastures are obviously fertilized and seeded, they rely on rain for growth. If there was a very large water storage, or even a number of significant ones, which extracted water from the river and we would use the reduction of water as the independent variable. The fact that we have only small farm water-holes (even though here are approximately 1,200 of them) gives us no scope to use changes in volume. The Tasmanian government has no record of quantities of water used by farmers.

The non-terrestrial catchment farmers, the oyster-growers in the estuary, rely on water in a different form, in a flow across their oyster stacks. Of course, the flow in the estuary is a function of rainfall throughout the catchment, plus any ground-water entering the main river and its tributaries before they reach the estuary, minus any water extractions that reduce the flow below. We have no data on the groundwater in the river basin. Whether or not the Little Swanport is a "losing" or a "gaining" river would be an important consideration in comparing upstream to downstream water flows.

In making our calculations we use the Bureau of Meteorology records for the most recent three years: 2005, 2006, 2007; plus the moving average. The records are taken at three recording stations just outside the catchment. The first is at Ross in the north-west. The second at Swansea in the north-east. The third is at Orford at the south. As is obvious in Table 10, the average rainfall varies across the catchment with the south being considerably wetter than the inland top of the catchment. However all of the catchment is dry – and hence is good Saxon merino country in normal conditions. The fact that Australia's mainland merino sheep are west of the Great Dividing Range is recognition that this breed of sheep are prone to footrot in high rainfall environments.

Table 10 Rainfall: Selected Sites, 2005 to 2007

Site	**Rainfall (millimetres)**			
	2005	**2006**	**2007**	**Average as of 2005**
Ross	630	357	353	503
Orford	727	408	405	679
Swansea	621	335	353	597

The data we obtained in our initial survey of farmers, which covered two non-drought years and the first year of the drought, showed far less damage costs than did our follow-up survey to capture the consequences of the second year of the drought. In the first year there were some replacement/preventative expenditures. They were for purchasing more-than-normal stock feed, growing more-than-normal feed on the farm, plus some other similar type costs. The total cost (which means a loss) for the catchment farmers was $1,553,000. This was for the year 2005-2006.

Far greater damage costs – which commenced with the drought conditions in 2006 – showed up in the year 2006-2007. In the latter year the replacement/preventative expenditures increased as farmers became more desperate in their attempt to reduce the extent of the damage and, more importantly, there were damage costs due to a loss in wool production, in fat lamb sales, and in beef production. We did not obtain sufficient data on the loss of cash crop income (mainly potatoes to document the loss on this aspect of farming); however our available data covers all grazing properties plus the sheep/cattle component of the mixed farms. It is an underestimate – not only for the reason that cash crops are excluded but for the extremely important reason that we have not considered anything other than one year. We have discussed this previously.

Before presenting the data for 2006-2007, it is very important to emphasise the fact that wool and meat prices have increased substantially recently. Fine and extra-fine wool (the "bread and butter" of the catchment) has reached price levels not seen for a considerable time. These price increases have cushioned – and quite significantly – the adverse impacts of the drought. They were obtaining higher prices for their meat and wool, yet their potential income was reduced – the opportunity cost of foregone production. For an example, a reduction in the wool clip where the selling prices is 1700c/kilo is a much greater loss than if it was to sell for 850c/kilo[2]. There is not one consistent story in the catchment. Particular farms which by the vagaries of nature have obtained more (of the scarce) rainfall than others endured "good economic" times. However, increased fuel and feed costs have had a dampening effect even on these farms. .

We can measure the *value of rainfall*, as damage costs, using a range of selling prices for wool and meat, and this would be a sensible approach in looking to the future. However, as a starting point it is constructive to present the damage costs as they occurred in 2006-2007 (where good prices prevailed).

Our data indicates that the loss of productivity for wool and meat combined (sheep and cattle) was in the order of $1,575,000. The total replacement/preventative expenditure during this year was approximately $1,780,000. The total damage cost was $3,355,000. Given that rainfall over the catchment was in the order of 60 percent of the normal year – and this was the case for two years running, the reduction in income to the catchment was approximately one-third of its normal state. Note, this is one-third of all income (including, importantly, that of the oyster-farmers) earned in a "normal"

[2] If the reduction is mainly a result in the shearing of less sheep, there are corresponding reduced shearing costs.

year in the catchment. If the oyster-farming income is excluded, the reduction to the terrestrial farmers is much higher as a percentage of catchment income.

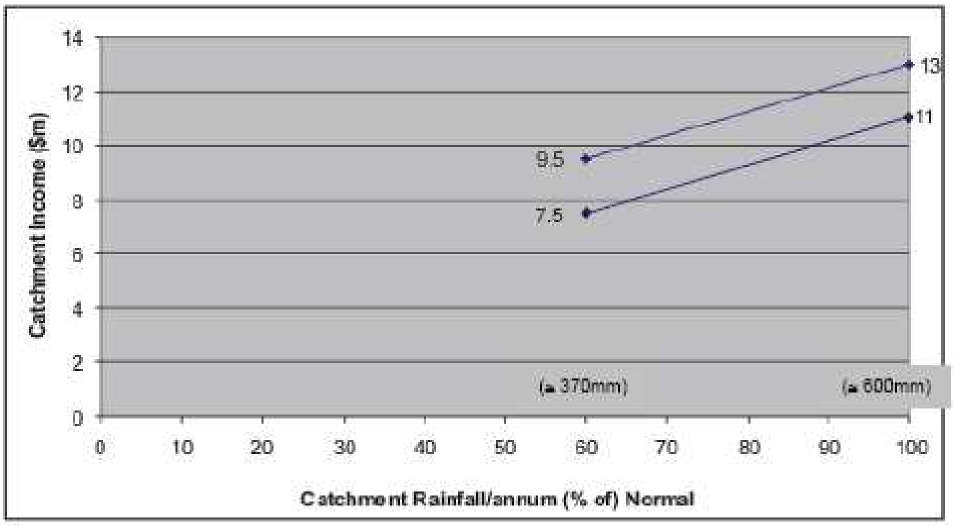


Figure 5 Rainfall and Income

We have drawn a straight line in Graph 2 to link the two parts. However this should not be taken to infer that there is a linear correlation between rain and income. More importantly, it should not be assumed that even worse drought conditions would result in a further linear decline in income (from $7.5 million). At some low level of rainfall the whole economy of the catchment tips to an unknown future. We have also drawn another line showing a decline in income from a higher total (approximately $13 million) falling to $9.0 million. This represents a state where wool and meat prices remain high as their recent maximum. The loss is greater. The area between the two lines can be considered a band, with the loss falling somewhere between the two.

What we have done is show the correlation between rainfall – as it falls over the whole catchment - and economic returns from the terrestrial farming in the whole catchment. That is an important piece of information. The les rain, the less sheep and cattle food, the less wool and meat for the market. To a lesser extent, because irrigation is an option, the value of crops like potatoes can be correlated to rainfall. We have said very little about rainfall and the oyster farmers making a living at the bottom of the catchment.

Oyster farming is a minor, but profitable fishery in Tasmania. The value of oysters produced per year is approximately $20 million. Of that, the Little Swanport estuary oyster production is significant, not only in the production and sale of mature oysters but in the production of immature oysters for sale to growers elsewhere in Tasmania. Oysters in the range of 20-30mm are in high demand to be ongrown. The firm Shellfish Culture has a nursery located in the Little Swanport estuary, which produces immature oysters for ongrowing by oyster farmers in Tasmania and South Australia. At “farm gate” prices, the Little Swanport estuary is capable of producing up to $7 million worth of oysters per annum, with seed oysters being more than half. Our modelling research has indicated that there could be a loss of oyster production of 12 percent if fresh water availability in the estuary was reduced by approximately 40 percent. Either a severe drought or the construction of a large impoundment upstream of the estuary could – while the drought persevered and /or until the dam water reached its maximum – cause a reduction in the estuary. What the economic value of water in a large impoundment would be can only be answered by reference to the use that water was put to. A large dam would not be of benefit to the grazing industry in the catchment as it requires a good spread of rainfall across the catchment.

Benefits and adoption

Overall, the results from the two objectives – increased knowledge of environmental flows to estuaries and the value of water to different users across a catchment – will underpin more informed management of freshwater environmental flows, especially to estuaries, by government managers involved in water allocation. The Tasmanian State Government Department of Primary Industry and Water (DPIW) Division of Water Resources has had a significant involvement in this project, including as a member of the Steering Committee. Additionally, they have received NHT NAP funding to develop and trial holistic environmental flow regimes for Tasmanian rivers and are collaborating with TAFI on estuarine flows, using the Little Swanport and Ringarooma estuaries as case studies. As a consequence of these collaborations, results from this research are likely to be adopted by DPIW and to inform their five-year review of the Water Management Plan for Little Swanport catchment.

Information on water use, water storage and extraction for agriculture across the catchment and environmental flows to estuaries was limited when the first water management plan was developed and this lack of knowledge created differences of opinion between primary producers in the catchment. The socioeconomic assessment of the catchment, especially of the farming community and the value of water to agricultural production during a normal year compared to during a severe drought has been of major interest to the Little Swanport Catchment Management Committee (most of who have some involvement in farming in the catchment). This is providing them with a better understanding of how their catchment functions economically and socially and will inform future planning by the catchment committee, including their involvement in the review of the water management plan.

There has been ongoing interaction between the researchers and the oyster farming companies operating in the estuary, especially Oyster Bay Oysters, for the duration of the project. Oyster Bay Oysters has provided ongoing support, both logistically and scientifically, as required. They have assisted with data collection, particularly collecting water and sediment samples in difficult conditions, and have provided their processing facility to process our samples. They have supplied temperature and salinity data from their in situ continuous loggers in the estuary and have routinely collected and processed phytoplankton samples. In turn, we have provided feedback to the oyster farmers on project progress. As a consequence, the results of the modelling of effects of different flow regimes and increased water allocation in the water management plan on oyster production have generally been accepted by the oyster farmers.

Similarly, interaction with agricultural farmers occurred throughout the project by both the economists as part of their surveys of farmers in the catchment, and by the regular attendance of the estuarine ecologists and often the economists at the Little Swanport Catchment Management Implementation Committee meetings to provide updates on the project. The ecologists also regularly communicated with Glamorgan

Spring Bay Council representatives and the project officer for the collaborative NRM South – Glamorgan Spring Bay Council project to develop a whole-of-catchment management plan for the Little Swanport catchment. These people regularly interacted with farmers in the catchment and were both a source of information on farming as well as passing on information about our research project to people in the catchment. As a result of this project, as well as the prior development of a water management plan for the catchment, land-based farmers are now more aware of the different users of water across the catchment and the competing interests for water allocation.

The model that has been developed to assess the effect of changing flow regimes on estuarine condition and oyster production in the Little Swanport estuary has wide application across southern Australia. With the input into the model of relevant hydrodynamic and environmental data from other estuaries, the relationship between oyster growth and freshwater flows in specific estuaries across southern Australia can be assessed.

Similarly, the economic water evaluation framework for differing uses across a catchment and the development of a set of monetary accounts has a much broader application than just the Little Swanport catchment; it is applicable to farmers and managers across southern Australia. These results are also to be released in book format, written in an easy-to-read style, with descriptions for the lay person of scientific and economic terms and methods, which provides a much wider audience for the research results than just researchers reading FRDC/LWA reports or the academic literature. The book is largely targeted at anyone interested in catchment activities and management.

An associated and unanticipated benefit of this project is the training of an early career researcher (Dr Jeff Ross) in ecosystem modelling with guidance from Dr Beth Fulton, an internationally recognised modelling expert, as part of the University and CSIRO collaborative QMS program. There is an increasing demand for qualified and experienced ecosystem modellers in Australia but few people trained in this area.

Further development

Additional projects and sources of funding

During the original 18-month period of this project, additional funding was sourced which has enabled aspects of the project to be extended. Ecological data from the estuary will continue to be collected for an additional 12 months after this FRDC/LWA project finishes.

- University of Tasmania Quantitative Marine Science Postdoctoral Fellowship sourced by Christine Crawford to continue the employment of the postdoc (Dr Jeff Ross employed on FRDC project), for an additional 18 months to complete the development of the estuarine hydrodynamic-biochemical model assessing effects of different flow regimes to the estuary.

- Australian Government funding through NRM South to DPIW Water Assessment Branch for Tasmanian Environmental Flows (TEFlows) Project. This project is further developing and testing a framework for holistic environmental flow regimes, which includes both high and low flows. The estuarine research component has been subcontracted to Jeff Ross and research is being conducted in the Little Swanport and Ringarooma estuaries. The final report will be completed by the end of 2009. A copy will be forwarded to FRDC as agreed.

- NRM South funded project to 'Develop and Implement a Framework to Measure Change in Marine, Coastal and Estuarine Water Quality', with Christine Crawford as the Principal Investigator. Two reports, *A framework for coastal and estuarine resource condition assessment* and *A baseline survey in the Southern NRM Region, Tasmania* for five estuaries including the Little Swanport are available at http://eprints.utas.edu.au/view/authors/Crawford,_CM.html

- Commonwealth Environment Research Facility (CERF) funding for the Landscape Logic Hub which aims to link land and water management to resource condition targets. The Tasmanian component of the hub is investigating the impact of land use, land management and previous landscape interventions on water quality and quantity. Christine Crawford and Jeff Ross are co-project leaders for the estuarine research component. Research, including the ongoing collection of environmental data, is being conducted in approximately 14 estuaries around Tasmania, including the Little Swanport estuary.

Benefits from these added sources of funding include monitoring data spanning three years instead of 12 months as originally planned. This has been particularly beneficial as the main sampling program for the FRDC project occurred during a period of prolonged drought (the Little Swanport catchment received no rain for three years (October 2005 – Nov/Dec 2008). When the first flood for three years occurred in Nov/Dec 2008, we had sufficient funding from these other projects to conduct an assessment of the effect of flood waters on the estuary. In particular, this has been the first opportunity to collect data on oyster growth rates after a flood. These results will enhance the data collected during the FRDC project.

We also developed and supervised two PhD studies which were associated with this project.

1. 'Ecology and life history characteristics of black bream, *Acanthopagrus butcheri*, in Tasmanian Estuarine Ecosystems' by Ryuji Sakabe. Supervisors: Christine Crawford, Jeremy Lyle and Alastair Richardson. The thesis has been accepted.
2. 'Paleoreconstruction of productivity in Little Swanport estuary' by Barry Gallagher. Field and experimental work has been completed, and writing up has commenced. Supervisors: Ted Lefroy, Jeff Ross, John Gibson and Christine Crawford.

Ryuji Sakabe's thesis was a study of the biological and ecological characteristic of black bream *Acanthopagrus butcheri,* an estuarine resident species, in the Little Swanport estuary and the Swan River. The distribution patterns of adult black bream varied between the Little Swanport estuary and the Swan River. Adults occurred mainly within the middle estuary, moving into the upper section of the Little Swanport estuary during the spawning season. By contrast, fish were largely distributed within the upper estuary of the Swan River throughout the year. This difference was probably due to more suitable habitats (i.e. submerged trees) and higher food availability in the upper estuary of the Swan River than in that part of the Little Swanport estuary. Juveniles appeared largely restricted to the upper estuary, but as they grew they became widely distributed within the estuary.

Black bream in these Tasmanian estuaries had a long life span of up to 30 years, with slow growth rate. Females grew larger than males. Based on gonadosomatic index and back-calculated birth dates, spawning occurred from early October to early January, with a peak in November–December. This study indicated that spawning was strongly influenced by the environmental conditions, especially salinity on the spawning ground. Successful spawning probably required salinities above approximately 10‰ and flood events during the spawning season negatively influenced spawning success. The ability to tolerate a wide range of salinities, a prolonged spawning season and long life span are the key strategies that have enabled the species to adapt successfully to this highly variable environment.

A study of the movements of individual fish using acoustic telemetry conducted in the Little Swanport Estuary demonstrated that adult black bream mainly utilised the upper and middle estuary regions, and showed that an upstream migration occurred from early August to middle January with a peak in November–December. There was no firm evidence that tagged fish moved out of the estuary, even during the periods of heavy freshwater discharge. However, during excessive freshwater inflows (flood events), fish moved or were washed away from the upper estuary region, and they remained the middle estuary region until water conditions in the upper estuary became favourable. Clearly, freshwater inflow was one of most important physical factors influencing movement and distribution of this species within the estuary.

Future research

Aspects of environmental flows to estuaries which were identified during this project as being important but not adequately covered are discussed below.

- The ecosystem box model was developed as a simple representation of the Little Swanport estuary to simulate the internal nutrient cycling processes amongst the major primary and secondary producers and the physical exchanges across the ocean boundary. It would be a mistake to think that the model and our understanding of the estuary's dynamics are complete. Unfortunately, we were only able to validate the model's performance under low flow conditions and, as such, when more field data becomes available under different river flow conditions, this model will be refined further, ensuring greater certainty in predictions.

- In this study we have focused on the cycling of nitrogen because it has long been recognised as the limiting nutrient in coastal systems; however, other nutrients such as silicate and phosphate can also be limiting. Although there was no evidence of silicate limitation in the empirical data or in the initial models runs when it was included, our data on silicate loads during floods and concentrations in the estuary are limited, and as such our findings are by no means conclusive. DIN:DIP ratios in the water column confirmed that the system is more likely to be nitrogen limited generally. However, unlike DIN, DIP didn't increase in concentration with river flow, indicating that the system may become phosphate limited during floods. A more complete understanding of the potential for nutrient limitation in Little Swanport would be best resolved by nutrient addition experiments and detailed flood sampling.

- This study also highlighted the importance of physical exchanges across the ocean boundary, and critically, the importance of river flow in dictating the magnitude of this exchange. This demonstrated the need for more detailed data at the ocean reference for the important state variables, so that fluxes across the estuary–ocean boundary can be more accurately predicted. Along the same lines, greater spatial resolution of the physical exchanges, and therefore, ecosystem responses within the estuary is also likely to improve the accuracy and utility of the model. In an effort not to make the model too complex, the system was represented as a single-well mixed box, and for the purposes of the study, we were able to predict system-wide averages reasonable well. The presence of both vertical and horizontal (along estuary) salinity gradients during significant river flows illustrated that more complex two-dimensional hydrodynamics were present in the estuary and consequently it is likely that some degree of increased spatial resolution would also improve the future utility of this model.

- Information on the importance of environmental flows required to support the migration of endemic freshwater fish through the estuary is very limited. All seven native freshwater species that naturally occur in the Little Swanport River – the endangered Australian grayling, two species of eels, two species of lampreys and two species of galaxids – have an obligate marine phase in their lifecycle and most move through the estuary as larvae. However, information on these species in the estuarine and marine environment is absent for some species and very scant for others. We had hoped to collect information through our larval fish sampling (details provided in a previous report) but this was limited to one species, *Galaxias maculatus*. Presumably we missed the migrations in our monthly sampling; more targeted sampling, both spatially and temporally, is required. This information is important to the determination of environmental water requirements for the river and the estuary and is relevant to water management plans for most Tasmanian catchments.
- The monetary value of ecosystem goods and services was not evaluated as fully as we had initially planned because of the severe drought conditions in the catchment. Choice modelling which involves surveying members of the catchment for the values they place on non-market goods and services, such as water for recreational use, fishing etc. would have provided biased results because of the severe – and in some cases catastrophic – financial conditions being experienced by farmers as a result of receiving no rain for three years. A monetary value of water in providing ecosystem goods and services is important to providing a balanced view of the value of water and environmental flows.

Planned outcomes

The outputs in relation to the ecological assessment of the estuary and the importance of environmental flows have been achieved. A report was produced on the estuarine ecological data and freshwater flows collected before the commencement of the FRDC project and a large quantity of relevant new data on estuarine ecology has been collected during this project. This information is underpinning an intended outcome of better knowledge of the function and processes of wave-dominated estuaries in south-eastern Australia and, in particular, the interaction between freshwater flows and estuarine health. The hydrodynamic–biochemical model to predict the effects of different flow regimes on estuarine ecology and oyster production will be beneficial to other southern Australian oyster growing regions. This new knowledge will lead to better management of estuaries, with the outcome of maintaining or improving their health and the sustainable commercial production of shellfish.

A specific planned outcome of this project was to provide data on environmental flows which will inform the five-year review of the Water Management Plan for the Little Swanport estuary. The first plan was released in draft form in September 2004 for public comment and the final plan was released in June 2006. Review of this plan will commence in 2011 and will use the information generated from this project.

The planned outputs in relation to the socioeconomic value of water across the catchment have been achieved (except for a detailed monetary valuation of ecosystem goods and services). The set of economic accounts for the value of water to different users across the catchment and the economic water evaluation framework with details on methodology will be of value to water resource managers across southern Australia who face similar issues of allocation of scarce water resources.

Results from the project have been communicated to the key stakeholders through presentations at committee meetings, at annual meetings of the LWA Environmental Water Allocation Program, at annual TAFI research overviews, at public meetings in the catchment, and at scientific conferences. Progress reports have been provided to the Little Swanport Catchment Management Committee and an article written for the LWA Rip Rap magazine. The book *The value of water in a drying climate*, which is at final draft stage, will provide results of the research to stakeholders and to a much wider audience than originally planned.

These outputs have also supported another planned outcome of increased stakeholder and community awareness of the environmental and economic benefits and costs of providing freshwater flows to the Little Swanport River, to primary production and to the estuary. This information will inform sustainable management practices within Little Swanport and other catchments in south-eastern Australia.

Conclusions

Christine Crawford and Tor Hundloe

From the information presented on measured and modelled changes in production of oysters in the estuary (Objective 1) and water accounts in the catchment (Objective 2), providing accurate data on the value of water to the different users across the catchment is clearly complex. The estuarine modelling is based on a number of assumptions, including that the estuary is well mixed and environmental parameters are uniform across the entire estuary. We were also only able to validate the model's performance under low flow conditions and, as such, this model will be refined further when more field data becomes available for higher river flow, leading to greater certainty in predictions. Similarly, the accounting for fresh water is subject to conjecture because of lack of freshwater flow data, such as the amount of water extraction across the catchment and flows to and from ground water.

We developed a water accounting framework for land-based activities, largely agriculture, and populated it with available data from the Little Swanport catchment as an example. The framework contains a comprehensive accounting of water flows and storage so that it is applicable to other catchments. However, there was not a sufficient number of farms of similar size and farming type to be able to construct a representative production function, a standard economic assessment method to estimate the economic value of various inputs. Additionally, very few farmers had data on volumes of water used on the farm. The oyster farmers in the estuary also were not able to provide data on the production of oysters in relation to the volume of freshwater entering the estuary because they adapt their growing methods according to the prevailing water quality conditions.

An important difference in the value of water to agriculture and aquaculture production that became apparent during our study was that agriculture largely relies on the quantity of water available, with essential nutrients provided in the soil or artificially from agricultural fertilisers. Aquaculture production, however, is reliant on the quality as well as the quantity of water flowing into the estuary. The freshwater contains nutrients, mainly nitrogen and phosphorous, to support the production of the phytoplankton food of the oysters, while the quantity of water delivered influences the amount of time that the nutrients remain in the estuary, and hence the time available for biological uptake. Silicates delivered in the freshwater are also essential for the production of diatoms. This issue of quantity versus quality makes comparisons between the different users even more complex.

For both the agricultural production in the catchment and the oyster production in the estuary, the drought conditions experienced during the three years of this project were initially problematic because floods were considered to be an important component of the annual water cycle, and we wanted to compare production between normal flow and flood conditions and to assess the importance of increased freshwater flow to the estuary. In the end, however, we used the drought conditions to provide a comparison of the value of water to agricultural and aquaculture production when water was plentiful to when it was severely limited during drought years. This provides estimates of the economic value of water at two (extreme) points on a continuum. It is not necessarily the case that the relationship is a linear one, however for policy-making purposes it could be assumed as such, particularly if an error band around the estimates is allowed for.

Across the catchment the loss of income to the catchment from wool production, fat lamb sales and beef production when rainfall was approximately 60% of a normal year was estimated to be $3,36 million, or approximately one-third of its normal state (cash crops were not included as there were insufficient data). This value was determined from the sum of preventative expenditure, replacement costs and loss of production incurred due to the drought. In the estuary nitrogen budgeting indicated that the increase in oyster harvest across two wet years (2004 and 2005) was estimated at ~43 kg N or a 12% increase relative to the two drought years of 2006 and 2007. This equates to a loss of approximately $500,000 in a severe drought year.

The loss in production in the estuary during the drought, which prevailed over much of the study period, was largely due to a lowering of the growth rate of the oysters; mortality was not observed to increase. Sufficient food was provided from oceanic waters and produced in the estuary to maintain the oysters but they were slower growing. During the drought with minimal freshwater flow into the estuary an influx of nutrients during winter indicated that nutrient-rich Southern Ocean waters penetrated up the East Coast of Tasmania and into the estuary. Thus, as a consequence of the drought, the oysters took longer to reach market size and condition. On land, however, many farmers were forced to destock and only keep essential breeding animals. The condition of grazing land was degraded in some areas as farmers struggled to maintain their herd. Crops either failed or produced less than normal and were not sown due to lack of water storage. Thus, the recovery time after the drought is likely to be greater on agricultural farms, taking several years to improve the condition of the grazing land and to restock with cattle and sheep, whereas in the estuary the recovery time is in the order of months. Recovery time also depends on the stocking density before the drought and whether the farmers were stocked to full capacity for good growing conditions or whether they maintained a lower stocking level which would provide a buffer during drought conditions. In the estuary where food for the oysters is produced throughout the estuary and transported across the farms by tide and wind driven water currents, the oyster farmers have reduced their stocking density and area available for farming so that they can produce a marketable product for most of the year under a variety of conditions.

In relation to environmental flows to the estuary, it is important to note that maintaining the low flows is most important. The transport model that was developed for freshwater flows through the estuary predicted a non-linear response to increasing river flow - flushing time (the amount of time that the freshwater and the nutrients in contains remain in the estuary) decreases quickly as river flow increases, but is relatively stable at high river flows. Ecosystem model simulations at different levels of base flows, based on this transport model, thus predicted that phytoplankton biomass, and consequently oyster growth, initially increases rapidly with base flow before the rate of increase slows to a steadier rate at higher flows. Therefore, there are greater benefits to the estuary per ML of river flow at low flow than at high flows. At low river flows primary producers have more time to take up the additional nutrient inputs from the river because the time to pass through the estuary is longer. In contrast, at higher flows, there is less time for biological uptake as the flushing time is shorter, and so the benefits are smaller per ML of river flow. For example, as base flows increases from 1-40 ML per day, oyster growth is predicted to increase by 11%, but another 11 % increase in growth only occurs when the base flow reaches 200 ML per day. The results of this study therefore support the cease to take requirements for low flows in the Water Management Plan for the catchment. However, the modelling predicted that the greatest benefits from river flow are achieved over the summer months because higher water temperatures significantly enhance the growth rates of phytoplankton and oysters.

The increased allocation of water for stock, domestic and irrigation purposes in the Water Management Plan (2006) from the existing total allocation of 3882 ML to a total catchment allocation capped at 6084 ML per year was shown by modelling to be unlikely to have a significant impact on the estuary for average and dry years. Modelling conducted using very dry flow conditions, as experienced in 2007, however, predicted that water harvesting during summer to the increased full allocation would lead to a decline in estuarine nutrient and phytoplankton concentrations and hence oyster growth responses. However, taken across the whole year the changes due the increased allocation would be relatively small, and fall within the limits of uncertainty inherent in the model simulations. Nevertheless, these results do imply that harvesting water during a very dry year is more likely to affect the estuary, especially during the summer months.

Although this research has centred on the Little Swanport catchment, the techniques developed are of relevance to many catchments across southern Australia. The biogeochemical model can be applied in other estuaries where there is sufficient local data, particularly in terms of hydrodynamics. The nutrient budget process can also be used in other estuaries with relevant local nutrient data available. The water evaluation framework developed for the catchment provides a generic template for catchments to assess the value of water to different users across a catchment. Data requirements, survey methods and types of analyses, along with likely issues and potential difficulties to water accounting are discussed.

The results clearly show that the profitability of both agriculture on land and aquaculture in the estuary are affected by changing freshwater flows. With changing climate regimes and predictions for dryer conditions on the east coast of Tasmania, as well as more extreme events, catchment communities will need to work closely together to protect and share scare water resources. Having a better understanding of the quality and quantity of water across the catchment and accounting for water use will be essential to this process.

References

Alber M, Sheldon JE (1999) Use of a date-specific method to examine variability in the flushing times of Georgia estuaries. Estuarine, Coastal and Shelf Science 49:469-482

Aleem AA (1972) Effect of river outflow management on marine life. Marine Biology 15:200-208

ARMCANZ, ANZECC (1996) National Principles for the Provision of Water for Ecosystems, Sustainable Land and Water Resources Management Committee, Subcommittee on Water Resources, Occasional Paper SWR No. 3

Arthington AH, Pusey BJ (2003) Flow restoration and protection in Australian rivers. River Research and Applications 19:377-395

Arthington AH, Pusey GJ (1993) Instream-flow management in Australia; methods, deficiencies and future directions. Australian Biologist 6:52-60

Australian Bureau of Statistics (2006). Water Account Australia 2004-5 Cat. No. 4610.0. Canberra, AGPS.

Australian Bureau of Statistics (2007). An experimental monetary water account for Australia. Canberra. ABS Cat. No 4610.0.55

AWR (2005) Australian Water Resources Level 2 key finding brochure. Australian Government national Water Commission, Canberra, available at http://www.nwc.gov.au/www/html/515-australian-water-resources-2005-level-2-key-findings-brochure.asp

Ayres, R. (1978). Resources, Environment, and Economics: Applications of the Materials/ Energy Balance Principle. New York., John Wiley & Sons.

Bain, D. (2008). Climate change and water: How water accounts can help our understanding. UNSD Conference on Climate change and Official Statistics. Oslo, April 2008. Paper for Session 3. Centre of Environment and Energy Statistics, Australian Bureau of Statistics

Border Rivers-Gwydir Catchment Authority (2008). "Calculating your own water budget." http://brg.cma.nsw.gov.au/index.php?page=calculating-your-own-water-budget. New South Wales Government

Boynton WR, Kemp WM, Keefe CW (1982) A comparitive analysis of nutrients and other factors influencing estuarine phytoplankton production. In: Kennedy VS (ed) Estuarine Comparisons. Academic Press

Brown MR, McCausland MA (1999) Increased production of juvenile Pacific oysters (*Crassostrea gigas*) through supplementary feeding. Final Report to FRDC, Project 94/83, CSIRO Marine Research, Hobart

Cameron, J. (1997). Applying socio-ecological economics: A case study of contingent valuation and integrated catchment management. Ecological Economics **23**(2) 155-165

Capone DG (1988) Benthic nitrogen fixation. In: Blackburn TH, Sorensen J (eds) Nitrogen Cycling in Coastal Marine Environments. John Wiley, Chichester, p 85-123

Clementson LA, Harris GP, Griffiths FB, Rimmer DW (1989) Seasonal and inter-annual variability in chemical and biological parameters in Storm Bay, Tasmania. 1.

Physics, chemistry and the biomass of components of the food-chain. Australian Journal of Marine and Freshwater Research 40:25-38

Cranford PJ, Strain PM, Dowd M, Hargrave BT, Grant J, Archambault MC (2007) Influence of mussel aquaculture on nitrogen dynamics in a nutrient enriched coastal embayment. Marine Ecology-Progress Series 347:61-78

Crawford C, Mitchell I, Brown A (1996) Predictive modelling of carrying capacities of oyster (*Crassostrea gigas*) farming areas in Tasmania. Final Report to the Fisheries Research & Development Corporation (FRDC), DPIF, Marine Research Laboratories, Hobart

Crawford C, Neira FJ, White C (2006) Environmental Flows in the Little Swanport Estuary. NHT Final Report 46932, Tasmanian Aquaculture and Fisheries Institute, Hobart

Crosby MP, Gale LD (1990) A review and evaluation of bivalve condition index methodologies with suggested standard method. Journal of Shellfish Research 9:233-237

Dinamani P (1987) Gametogenic patterns in populations of Pacific oyster, *Crassostrea gigas*, in Northland, New Zealand. Aquaculture 64:65-76, University Press

Dixon JA and Hufschmidt M. (1986) Economic valuation techniques for the environment : a case study workbook. Baltimore : Johns Hopkins

DPIWE, (2003). Little Swanport Catchment: Water Resources Information Package. Department of Primary Industries, Water and Environment (Water Assessment and Planning Branch) June 2003. Tasmania

DPIWE, (2005). Draft Little Swanport Catchment Water Management Plan. Summary of Public Representations. Report prepared pursuant to S26 OF THE WATER MANAGEMENT ACT 1999. Prepared for The Resource Planning and Development Commission by Water Assessment & Planning Branch Department of Primary Industries, Water and Environment. July 2005

DPIWE (2006) Little Swanport Catchment Water Management Plan. Water Policy and Planning Branch, Department of Primary Industries and Water, Hobart

DPIWE (2007a). "Little Swanport Catchment: Waterways monitoring report." www.dpiw.tas.gov.au/inter.nsf/Attachments/WWEB-6MJ3GP/$FILE/Little%. Water Assessment Branch 2007 ISSN: 1835-8489

DPIWE (2007b). "Hydrophysical characterisation of the Little Swanport River catchment." www.dpiw.tas.gov.au/inter.nsf/Attachments/SSKA-6YT2XG/. No other info.

Drenen A (2003) Land use mapping at catchment scale, Tasmanian Report. Department of Primary Industries, Water and Environment, Hobart.

Duarte CM (1990) Seagrass nutrient content. Marine Ecology-Progress Series 67:201-207

Dunlop, M. (2003). Australian water use statistics. Canberra, Australia. Working Paper Series 01/03, CSIRO Sustainable Ecosystems

Dyer KR (1973) Estuaries: A physical introduction. John Wiley and Sons, New York

Eyre B (1998) Transport, retention and transformation of material in Australian estuaries. Estuaries 21:540-551

Eyre B, Twigg C (1997) Nutrient behaviour during post-flood recovery of the Richmond River Estuary, northern NSW, Australia. Estuarine, Coastal and Shelf Science 44:311-326

Fasham MJR, Ducklow HW, McKelvie SM (1990) A nitrogen-based model of plankton dynamics in the oceanic mixed layer. Journal of Marine Research 48:591-639

Fenton JD, Keller RJ (2001) The calculation of streamflow from measurements of stage. Technical Report No. 01/6, Cooperative Research Centre for Catchment Hydrology

Finlayson BL, McMahon TA (1988) Australia v the world: a comparative analysis of streamflow charactristics. In: Warner RF (ed) Fluvial Geomorphology of Australia. Academic Press, Sydney

Global Water Partnership Technical Advisory Committee (TAC) (2000). "Integrated Water Resources Management." TAC Background Paper No. 4. Global Water Partnership. Stockholm.

Gordon JDC, Boudreau PR, Mann KH, Ong JE, Silvert WL, Smith SV, Wattayakom G, Wulff F, Yanagi T (1996) Biogeochemical Modelling Guidelines, LOICZ/R&S/95-5, LOICZ, Texel, The Netherlands

Halliday IA, Robins JB, Mayer DG, Staunton-Smith J, Sellin MJ (2008) Effects of freshwater flow on the year-class strength of a non-diadromous estuarine finfish, king threadfin (*Polydactylus macrochir*), in a dry-tropical estuary. Marine and Freshwater Research 59:157-164

Hansen JW, Udy JW, Perry CJ, Dennison WC, Lomstein BA (2000) Effect of the seagrass *Zostera capricorni* on sediment microbial processes. Marine Ecology Progress Series 199:83-96

Harris G, Nilsson C, Clementson L, Thomas D (1987) The water masses of the east-coast of Tasmania - Seasonal and interannual variability and the influence on phytoplankton biomass and productivity. Australian Journal of Marine and Freshwater Research 38:569-590

Howarth RW, Marino R (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnology and Oceanography 51:364-376

Hufschmidt, MM (1983) Environment, Natural Systems, and Development: An Economic Valuation Guide. Baltimore : Johns Hopkins University Press *

Hughes L (2003) Climate change and Australia: Trends, projections and impacts. Austral Ecology 28:423-443

James D (1994) The Application of Economic Techniques in Environmental Impact Assessment. Dordrecht The Netherlands, Kluwer Academic Publishers

Kennish MJ (2002) Environmental threats and environmental future of estuaries. Environmental Conservation 29:78-107

Leaman, D (2005). Water: Facts, Issues and Problems, Leaman Geophysics, Hobart

Little Swanport Catchment Committee (2002). Little Swanport Catchment Management Plan. May 2002, Report complied by Little Swanport Catchment Committee

Loneragan NR, Bunn SE (1999) River flows and estuarine ecosystems: Implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. Australian Journal of Ecology 24:431-440

Madden CJ, Kemp WM (1996) Ecosystem model of an estuarine submersed plant community: Calibration and simulation of eutrophication responses. Estuaries 19:457-474

Markwick, G. (2002). Water requirements for sheep and cattle. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/96273/water-requirements-for-sheep-and-cattle.pdf. Agfact A0.5.4 DPI NSW Agriculture

Mitchell IM (2001) Relationship between water quality parameters (nutrients, seston, chlorophyll *a*), hydrodynamics and oyster growth in three major Pacific oyster (*Crassostrea gigas*) growing areas in southern Tasmani (Australia). M.Sc. thesis, University of Tasmania

Moll A (2000) Assessment of three-dimensional physical-biological ECOHAM1 simulations by quantified validation for the North Sea with ICES and ERSEM data. ICES J Mar Sci 57:1060-1068

Mount R, Lucieer V, Lawler M, Jordon A (2005) Mapping of estuarine and marine habitats in the southern NRM region. NHT Final Report 46937, Tasmanian Aquaculture and Fisheries Institute, Hobart

Murphy R, Crawford C, Barmuta L (2003) Estuarine health in Tasmania, status and indicators: water quality. Technical Report 16, Tasmanian Aquaculture and Fisheries Institute, Hobart

Murray AG, Parslow JS (1999) Modelling of nutrient impacts in Port Phillip Bay - a semi-enclosed marine Australian ecosystem. Marine & Freshwater Research 50:597-611

Murray AJ, Parslow JS (1997) Port Phillip Bay integrated model: final report, CSIRO, Canberra

Officer CB, Ryther JH (1980) The possible importance of silicon in marine eutrophication. Marine Ecology Progress Series 3:83-91

Potts J (2004) Quantification of sediment-water nutrient and oxygen flux rates in Little Swanport Inlet, Tasmania. Internal Report, Department of Environment and Conservation (NSW), Sydney, Australia

Puckridge JT, Sheldon F, Walker KF, Boulton AJ (1998) Flow variability and the ecology of large rivers. Marine and Freshwater Research 49:55-72

Ren JS, Marsden ID, Ross AH, Schiel DR (2003) Seasonal variation in the reproductive activity and biochemical composition of the Pacific oyster (*Crassostrea gigas*) from the Marlborough Sounds, New Zealand. New Zealand Journal of Marine and Freshwater Research 37:171-182

Resource Planning and Development Commission (2006). Report on the Draft Little Swanport Catchment Water Management Plan 2004. Prepared and published by: Resource Planning and Development Commission. Hobart. Tasmania. May 2006.

Robins JB, Halliday IA, Staunton-Smith J, Mayer DG, Sellin MJ (2005) Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. Marine and Freshwater Research 56:343-360

Rocha C, Galvao H, Barbosa A (2002) Role of transient silicon limitation in the development of cyanobacteria blooms in the Guadiana estuary, south-western Iberia. Marine Ecology-Progress Series 228:35-45

Rosenberg DM, Bodaly RA, Usher PJ (1995) Environmental and social impacts of large scale hydroelectric development: who is listening? Global Environmental Change 5:127-148

Ryan PJ, Harleman DFR (1973) An analytical and experimental study of transient cooling pond behaviour. Technical Report 161, MIT

Sinclair Knight Merz (2004) Little Swanport Catchment: Water balance model and scenario assessment. Sinclair Knight Merz, Armadale, Victoria

Strickland JD, Parson TR (1972) A Practical Handbook of Seawater Analysis. Ottawa, Canada

Taylor GI (1953) Dispersion of soluble materials in solvent slowly flowing through a tube. Proceedings of the Royal Society of London A219:186-203

Tharme RE (2003) A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19:397-441

United Nations (2003). SEEA Integrated Environmental and Economic Accounting 2003. Studies in Methods Handbook of National Accounting. Series F, No.61, Rev.1 (ST/ESA/STAT/SER.F/61/Rev.1)

United Nations (2006). Draft Handbook on Environmental and Economic Accounting for Water Resources. New York, United Nations Statistical Division.

Valiela I (2006) Global Coastal Change. Blackwell Publishing, MA, Oxford, Victoria

Vardon, M., M. Lenzen, et al. (2007). Water accounting in Australia. Ecological Economics **61**(4) 650-659

Welsh DT (2000) Nitrogen fixation in seagrass meadows: Regulation, plant-bacteria interactions and significance to primary productivity. Ecology Letters 3:58-71

Whitefield AK, Wooldridge TH (1994) Changes in freshwater supplies to southern African estuaries: some theoretical and practical considerations. In: Dyer KR, Orth RJ (eds) Changes in fluxes in Estuaries: Implications from science to management. Frendensberg, Denmark

Wilson RS, Cohen BF, Poore GCB (1993) The Role of Suspension-feeding and Deposit-feeding Benthic Macroinvertebrates in Nutrient Cycling in Port Phillip Bay. Report No. 10, Museum of Victoria, Melbourne

Yanagi T (2000) A simple method for estimating VX from mixing equations in a 1-dimensional steady state system for LOICZ biogeochemical modeling. In: Dupra V, Smith SV, Marshall Crossland JI, Crossland CJ (eds) Estuarine systems of the east Asia region: carbon, nitrogen and phosphorus fluxes. LOICZ Reports and Studies No. 16. LOICZ, Texel, The Netherlands

Appendix 1 Intellectual Property

There are no intellectual issues associated with the project.

Appendix 2 Staff

Principal Investigator: Christine Crawford
Co-Investigators: Tor Hundloe, Colin Shepherd
Post-Doc Estuarine ecology: Jeff Ross
Technical Assistant for Objective 1: Sam Foster
Environmental economist: Peter Daniels
Research assistants with Tor Hundloe: Tara Cully, Amy White,
Michelle Werner, Eloise Weldon

Appendix 3A Model processes

The model uses well understood relationships for key ecological processes. All of the plants (phytoplankton, microphytobenthos and seagrass) photosynthesise, taking up nutrients from the water column (phytoplankton) or sediments (microphytobenthos and seagrass), and growing at rates determined by light and nutrient availability. Zooplankton grazing results in both phytoplankton losses and zooplankton growth. Oyster grazing results in phytoplankton and detrital losses. Oyster biomass is held constant throughout the year based on industry estimates, with oyster growth removed during harvest. The biomass value takes into account industry estimates of mortality. All living components are subject to mortality, and together with faecal production produce labile detritus, which breaks down at prescribed rates to form dissolved inorganic nitrogen or refractory detritus and dissolved organic nitrogen. Nitrification and denitrification can lead to a loss of available nitrogen from the system.

Primary production

The growth rate of each of the primary producers (Pgrowth, SGgrowth, MPB growth) is a function of the maximum growth rate, multiplied by a nutrient (hN) and a light (hI) limitation factors, and for seagrass, a space (hS) limitation factor. For example, the equation for seagrass is:

$$SGgrowth = mumSG \cdot hN \cdot hI \cdot hS \cdot SG$$

Nutrient limitation (hN): the model used the Monod formula to describe the relationship between nutrient concentration and plant growth rate:

$$hN = \frac{DIN}{kN\_x + DIN}$$

where kN_x is the half saturation constant for nitrogen limited growth, and x represents P, SG or MPB.

Light limitation (hI): a simple bilinear model is used in which growth rate increases linearly with light levels at low intensities and saturates at higher light levels:

$$hI = \min\left[\frac{I}{kI\_x}, 1\right]$$

where kI_x is the light saturation intensity for growth of primary producer x. In this model, phytoplankton growth rate depends on mean water column light intensity ($I = I_{mean}$; see below for calculation), and seagrass and microphytobenthos depend on bottom light intensities ($I = I_{bottom}$).

Space limitation (hS): a maximum biomass of seagrass (SGmax) is assumed due to crowding and/or self-shading, with the growth rate declining as this maximum is approached:

$$hS = \left(1 - \frac{SG}{SG\max}\right)$$

Secondary production

Zooplankton and oyster grazing on phytoplankton and detritus (oysters only) lead to an increase in their biomass and the production of detritus and excretion of dissolved inorganic nitrogen. The grazing rate is based on a Holling type-II functional rate relating ingestion rate to food density with saturation at high food concentrations. The equation for zooplankton grazing which only feed one food type, phytoplankton is:

$$ZgrazeP = \frac{Z \cdot P \cdot CRZ}{\left(1 + \frac{CRZ \cdot EZ \cdot P}{mumZ}\right)}$$

where *CRZ* is a measure of the volume cleared by the grazer per unit time, *mumZ* represents the maximum growth rate for zooplankton, and *EZ* represents the growth efficiency (i.e. proportion of ingested prey turned into biomass) of zooplankton. Oysters feed on multiple food sources (phytoplankton and detritus) and are assigned different growth efficiencies on detritus (*EO_D*) than on phytoplankton (*EO_P*). We assume growth efficiency on detritus is half of that on phytoplankton. Therefore, oyster grazing on phytoplankton is represented as:

$$OgrazeP = \frac{O \cdot P \cdot CRO}{\left(1 + \frac{CRO \cdot (EO\_P \cdot P + EO\_D \cdot DL)}{mumO}\right)}$$

and oyster grazing on detritus as:

$$OgrazeDL = \frac{O \cdot DL \cdot CRO}{\left(1 + \frac{CRO \cdot (EO\_P \cdot P + EO\_D \cdot DL)}{mumO}\right)}$$

Increases in grazer biomass are obtained by multiplying the grazing rate by the relevant growth efficiency:

$$Zgrowth = ZgrazeP \cdot EZ$$
$$Ogrowth = OgrazeP \cdot EO\_P + OgrazeDL \cdot EO\_DL$$

Mortality

Phytoplankton mortality due to oyster and zooplankton grazing is defined explicitly above. All other loss rates in the model are proportional either to biomass concentration (linear '*mL*') or to concentration squared (quadratic '*mQ*'). Phytoplankton which have sedimented out are subject to higher loss rates due to either an unfavorable environment or to removal by deposit and/or filter feeders (i.e. other than oysters). This is modelled as linear mortality:

$$Pmort = mLP.P$$

A quadratic mortality term is used for the losses of microphytobenthos and zooplankton:

$$Zmort = mQZ \cdot Z^2$$
$$MPBmort = mQMPB \cdot MPB^2$$

Seagrasses are assigned linear mortality. Although epiphytes that can coat seagrasses are not modelled explicitly, their effects on seagrass mortality due to overgrowth is accounted for with an additional seagrass mortality term (*mSSG*) proportional to DIN:

$$SGmort = mLSG.SG + DIN \cdot mSSG \cdot SG$$

Detritus production and excretion

The proportion of food grazed by zooplankton that is not converted into new biomass (i.e. 1 – *EZ*) is either released as detritus (through messy feeding or as faecal pellets), or metabolised and the inorganic nitrogen excreted. The model assigns a fixed proportion (*FDGxx*) of the total waste to detritus and a fixed proportion of mortality losses (*FDMxx*) to detritus production. For oysters, the proportion of the total waste to detritus is higher when feeding on detritus (*FDLO*) compared with phytoplankton (*FDGO* = 0.5 *FDLO*):

$$ZprodDL = (1 - EZ) \cdot FDGZ \cdot ZgrazeP + FDMZ \cdot Zmort$$
$$OprodDL = (1 - EO\_P) \cdot FDGO \cdot OgrazeP + (1 - EO\_DL) \cdot FDLO \cdot OgrazeDL$$

All of the direct mortality losses by primary producers are converted to labile detritus.

Grazer losses that are not assigned to labile detritus are assigned to dissolved inorganic nitrogen:

$$Zexcret = (1 - EZ) \cdot (1 - FDGZ) \cdot ZgrazeP + (1 - FDMZ) \cdot Zmort$$
$$Oexcret = (1 - EO\_P) \cdot (1 - FDGO) \cdot OgrazeP + (1 - EO\_DL)(1 - FDLO) \cdot OgrazeDL$$

Remineralisation

Labile detritus (DL) rapidly breaks down at a fixed rate (rDL) to produce dissolved inorganic nitrogen (DIN), but some of it is converted to refractory detritus (FDR_DL) and dissolved organic nitrogen (FDON_DL). The refractory detritus breaks down slowly at a fixed rate rDR to produce DIN, with some forming dissolved organic nitrogen (DON). The DON breaks down at a slightly faster fixed rate (rDON). Therefore:

DLremin = DL·rDL

DRremin = DR·rDR
DONremin = DON·rDON
DLprodDR = DL·rDL·FDR_DL
DLsolDON = DL·rDL·(1-FDR_DL)·FDON_DL
DRsolDON = DR·rDR.·FDON_DL

In the sediment, a specified fraction of the DIN produced as ammonia following remineralisation of detritus can be nitrified, producing DIN as nitrate, which in turn can be denitrified to produce nitrogen gas (N_2), which is biologically unavailable and represents a permanent sink of nitrogen for the system. Rates of nitrification and denitrification depend on the redox state of the sediments, with nitrification occurring under oxic and denitrification under anoxic conditions. The semi-empirical representation of these processes developed by Murray & Parslow (1997) is used here. The model partitions the ammonia produced through remineralisation among ammonia, nitrate and N_2 gas according to the net sediment respiration rate (ReminNet), which is equivalent to the oxygen stress in the sediment. The fraction of ammonia produced which is nitrified (NE) decreases linearly from a maximum value (Dmax) at zero respiration to zero at or above a sediment respiration rate of RO. Conversely, the fraction of nitrate produced which is denitrified (DE) increases from zero at zero respiration to 100% at or above a remineralisation rate RD. Therefore, the fraction of ammonia denitrified increases to a maximum at remineralisation rate RD, before decreasing to zero when remineralisation rates reach RO.
Remin = DLremin + DRremin + DONremin
ReminNet = Remin – MPBgrowth

$$NE = Dmax\left(1 - \frac{ReminNet}{RO}\right)$$

$$DE = \min\left(\frac{ReminNet}{RD}, 1\right)$$

Nitrification = ReminNet·NE
Denitrification = Nitrification·DE

Appendix 3B Numerical stability

The model equations are integrated in time using a 4th order Runge-Kutta integrator. Although the time unit used in the formulation of the model equations is days, the choice of dt, the number of times the calculations are run per day, is critical in ensuring numerical stability in the model outputs. To determine the appropriate dt, differences in the output of the model run under 'idealised conditions' (see below) for two years were compared using dt = 1, 2, 4, 8, 16 and 32. It was clear that the results converged at a DT of 8 and above (Figure 26) and as such DT was set at 16 for all subsequent model runs.

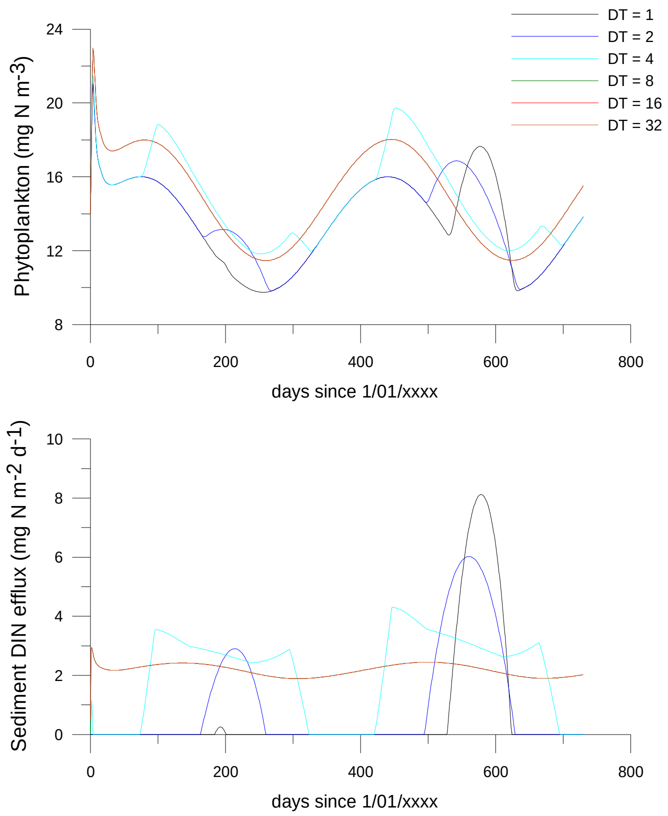


Figure 26 Comparison of the model results for phytoplankton biomass and sediment DIN efflux with different time intervals (DT) between numerical calculations. Numerical instability was clearly evident for DTs = 1, 2 and 4. Using a DT of 8 and above provided identical results. The DT was set at 16 for subsequent model runs.

Appendix 3C Sensitivity analysis

The model was run under 'idealised conditions' for two years, and the results for the second year were analysed for changes in the state variables, by comparing to a 'control' simulation with no changes in the parameters or forcing functions. Under idealised conditions, river flow was kept at a constant 5000 m^3 per day, and thus, ocean exchanges were held constant as defined by the transport model. Initial values for the state variables, derived from the model spin up described above, were used.

Parameters

The sensitivity of the model to parameter values was assessed by varying each parameter in the model by 20% and analysing the change in each state variable. Although there are limitations to sensitivity analysis (e.g. difficult to assess synergistic effects), it is a very useful tool for examining the dependence of the model on specific parameters, and identifying those parameters that potentially contribute most to uncertainty in model predictions. The sensitivity of each state variable to each parameter was calculated using the equation derived by Murray & Parslow (1997):

$$Sensitivity = \frac{V(1.2p) - V(0.8p)}{V(p)0.2}$$

where $V(1.2p)$ is the mean of the state variable (V) when parameter p was increased by 20% and $V(0.8p)$ is the mean value when the parameter was decreased by 20%. $V(p)$ is the mean value of the state variable when there is no change in the parameter. If this normalised sensitivity is close to 1, the change in V is proportional to the change in p. If the sensitivity is close to 2, V is proportional to p^2.

The most sensitive parameters in the model are the maximum growth rates (mum P, mum Z, mum MPB and mum SG), the filtration rate (CR Z) and growth efficiency (E Z) of zooplankton, the nutrient saturation parameter (kn P, kn MPB and kn SG), mortality rates (mQ Z, mQ MPB, mL SG and mS SG), the phytoplankton sinking rate (wP), maximum denitrification efficiency (Dmax), maximum standing crop of seagrass (SGmax), DON breakdown (rDON), and the proportion of detrital breakdown producing refractory detritus (FDR DL) and DON (FDON D). Notably, all of the major pools were relatively insensitive to the oyster parameters (mum O, CR O and E O), with the exception of oysters themselves, which are sensitive to their filtration rates (CR O) and growth efficiency (E Z). Other parameters that don't appear to play and important role are the light saturation parameters (ki P, ki SG and ki MPB), light attenuation coefficients (k_W, k_{IS}, k_P, k_{DON}, k_D), and the burial rate of refractory detritus (DR burial rate).

The principal factors controlling the biomass of phytoplankton are their sinking rate (wP), maximum growth rate (mum P), and the grazing by zooplankton (which in turn is dependent on CR Z, mum Z and mQ Z). The breakdown rate of the large pool of

DON also plays an important role in controlling phytoplankton biomass. To a lesser extent, maximum denitrification efficiency (Dmax) and the nutrient half saturation constant for phytoplankton (kn P) and microphytobenthos (kn MPB) also play a role in phytoplankton dynamics.

The DON pool is insensitive to all parameters with the exception of its breakdown rate rDON. This is because a balance between river inputs and oceanic exchange rather than DON production from detritus largely controls water column DON. In contrast, the DON pool in the sediments is controlled by a balance between DON production from a much larger pool of detritus, and losses due to its breakdown. The DON pool in the sediments is most sensitive to the parameter FDON_D, which controls the proportion of detritus converted to DON, and to a lesser extent FDR_LD, which controls the proportion of detritus that is refractory and its breakdown rate (rDON). The sediment DON pool is also sensitive to other parameters that control the rate of production and delivery (sinking rates) of detritus from the water column.

Table 10 Sensitivity of the major model pools (annual averages) to variation in parameters. These pools in the water column are phytoplankton (P), zooplankton (Z), oysters (O), inorganic nitrogen (wcDIN), dissolved organic nitrogen (DONw) and labile detritus (DLw). The major pools in (or on) the sediments are seagrass (SG), microphytobenthos (MPB) and dissolved inorganic nitrogen (sedDIN).

	P	Z	O	SG	MPB	wcDIN	sedDIN	DONw	DLw
CR O	-0.02	-0.01	0.19	-0.01	0.00	0.02	0.00	0.00	-0.04
CR Z	-0.58	0.26	-0.09	-0.62	-0.18	1.26	-0.28	0.00	0.47
E O	0.00	0.00	0.20	-0.01	-0.01	0.00	-0.01	0.00	0.00
E Z	-0.14	0.54	-0.02	-0.13	-0.07	0.23	-0.09	0.00	0.02
ki MPB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ki P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ki SG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kn MPB	-0.28	0.10	-0.04	-0.31	-0.60	0.70	-0.08	0.00	0.18
kn P	-0.22	-0.14	-0.04	-0.44	-0.12	0.90	-0.19	0.00	-0.23
kn SG	0.03	0.02	0.01	-0.38	0.30	0.01	0.27	0.00	0.03
PmL	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
ZmQ	0.48	-0.65	0.08	0.52	0.17	-0.99	0.25	0.00	-0.29
mL SG	0.02	0.01	0.01	-0.72	0.20	0.01	0.13	0.00	0.02
MQ MPB	0.01	0.01	0.00	0.03	-0.92	0.00	0.06	0.00	0.01
mS SG	0.01	0.01	0.00	-0.35	0.09	0.00	0.07	0.00	0.01
mum MPB	-0.01	-0.01	0.00	-0.05	0.86	-0.01	-0.09	0.00	-0.02
mum O	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
mum P	0.51	0.33	0.09	1.01	0.24	-2.09	0.38	0.00	0.53
mum SG	-0.07	-0.04	-0.02	0.88	-0.69	-0.03	-0.63	0.00	-0.07
mum Z	-0.38	0.18	-0.06	-0.40	-0.11	0.79	-0.18	0.00	0.33
wDLR	-0.02	-0.01	-0.02	0.04	0.06	-0.01	0.07	0.00	-0.64
wKI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
wP	-0.60	-0.38	-0.12	-0.08	0.17	0.47	0.18	0.00	-0.64
porosity	-0.04	-0.02	-0.01	0.49	-0.35	-0.02	-1.42	0.00	-0.04
Q10	-0.04	-0.04	0.03	-0.02	-0.01	0.10	-0.02	0.00	0.03
FDG Z	-0.09	-0.05	-0.01	0.02	0.02	-0.03	0.02	0.00	0.37
FDM Z	-0.08	-0.05	-0.01	0.02	0.01	-0.03	0.02	0.00	0.34
FDOM DL	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.00
FDR LD	-0.08	-0.05	-0.01	-0.27	-0.47	-0.03	-0.55	0.00	-0.12
rDL	0.03	0.02	0.01	0.00	0.02	0.01	0.00	0.00	-0.20
rDOM	0.52	0.33	0.10	0.22	0.50	0.23	0.58	-0.19	0.58
rDR	0.02	0.01	0.00	0.07	0.12	0.01	0.13	0.00	0.02
RO	-0.03	-0.02	0.00	-0.01	-0.02	-0.01	-0.03	0.00	-0.03
RD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dmax	-0.27	-0.17	-0.05	-0.11	-0.25	-0.13	-0.30	0.00	-0.29
SGmax	-0.05	-0.03	-0.02	0.71	-0.55	-0.02	-0.50	0.00	-0.06
DR burial rate	-0.02	-0.01	0.00	-0.06	-0.11	-0.01	-0.13	0.00	-0.02
kP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kPAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kTSS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kDL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kDON	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kw	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Forcing functions

The sensitivity of the model to changes in the forcing functions with the greatest degree of uncertainty in their estimation was assessed, namely ocean boundary conditions for dissolved inorganic nitrogen (DINocean), phytoplankton (Pocean) and zooplankton (Zocean), the flushing time for when there was no river flow (constant k) and the DINriver vs. river flow relationship. For DIN, the ocean boundary condition was a seasonal relationship based on data collected in the most recent study by Crawford et al. (2006). Alternatively, there have been many more measurements of nitrate (but not ammonia and nitrite) at the same ocean reference site in the past (Crawford et al. 1996; Mitchell 2001; Murphy et al. 2003), as well as records back to 1940 from CSIRO's long-term monitoring site at Maria Island. When this data is aggregated across years to identify potential seasonal cycles, it is clear that there is a distinct winter peak at both the LSP ocean reference site and Maria Island (Figure 27). At Maria the peak levels are approximately double those measured at LSP and extend to later in the year.

To test the model's sensitivity to both of these scenarios, we had to assume that ammonia levels were constant at 13 mg N m^{-3} and that nitrite was present at a fixed ratio of nitrate levels based on the measurements by Crawford et al. (2006). The subsequent seasonal models for ocean DIN in each scenario are also shown in Figure 27. It is clear from the model outputs in Figure 28 that the model is very sensitive to changes in the ocean boundary conditions for DIN, more so in terms of seasonality than average concentrations. Compared to the standard run, the later onset of the winter peak in DIN concentrations in the ocean, predicted at the LSP ocean reference site and at Maria Island, leads to a dampening of the late summer phytoplankton bloom in the estuary. This is because there is a reduction in DIN imported from the ocean in summer. However, the increase in imported DIN in winter leads to the creation of secondary and larger peaks in winter phytoplankton due to the increase in imported DIN. This is also evidenced in the zooplankton response and oyster growth.

For phytoplankton (measured as chlorophyll-*a*), there were very few data points and no apparent seasonal patterns in the recent study by Crawford et al. (2006), so a constant ocean boundary condition of 7 mg N m^{-3} was initially adopted. However, if we aggregate data across all of the studies that have sampled chlorophyll-*a* at the ocean reference site, there does appear to be a propensity for elevated chlorophyll-*a* levels in late summer/early autumn and late winter/spring (Figure 29c). The variability evident in Figure 29c may reflect the strong interannual changes in the timing and magnitude of the blooms that has been documented in other studies on the east coast of Tasmania (Clementson et al. 1989; Harris et al. 1987). Satellite-derived chlorophyll-*a* concentrations can also be used to parameterise ocean conditions. Figure 30 shows a time (2003–08) versus latitude (148°E to 150°E) plot between 42.3°S and 42.5°S which corresponds to an area extending from the coast adjacent to the mouth of Little Swanport offshore. The plot highlights the greater chlorophyll-*a* concentrations inshore and the strong interannual variability.

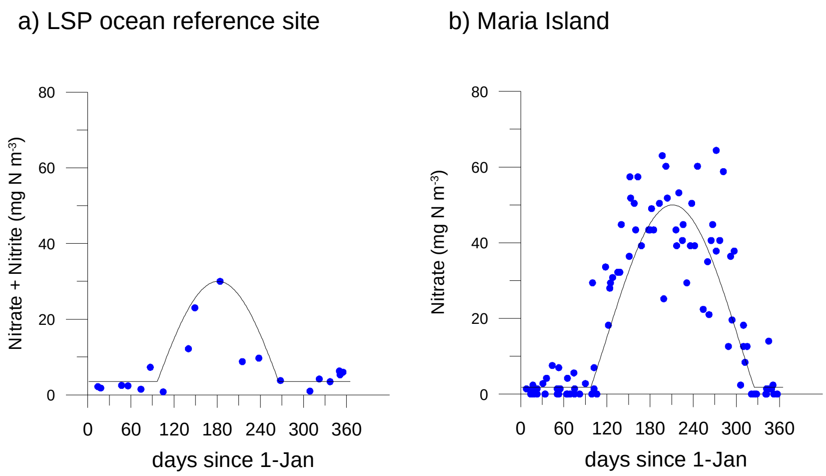


Figure 27 Nitrate observations aggregated from studies between 1990 and 2001 at Little Swanport (a), and between 1940 and 2006 at Maria Island (b). The subsequent seasonal models (black lines) used in the sensitivity runs are also shown.

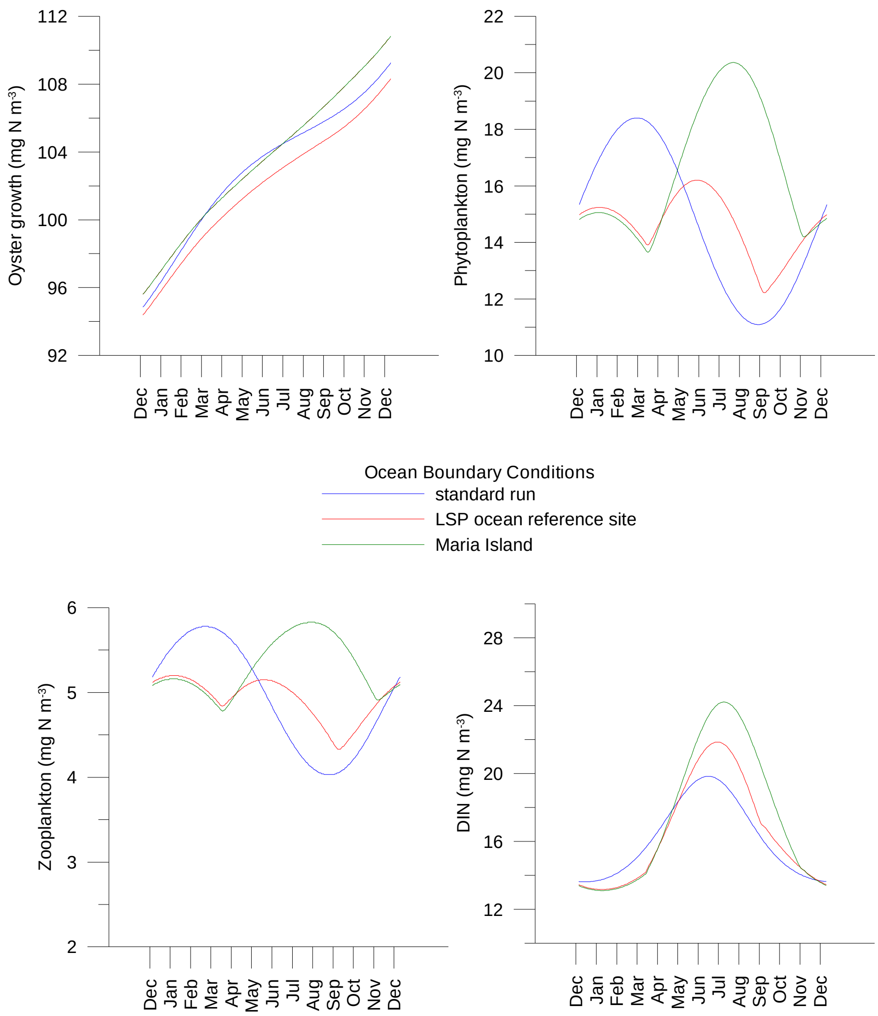


Figure 28 Comparison of model outputs for oyster growth, phytoplankton, zooplankton and dissolved inorganic nitrogen (DIN) under different oceanic boundary conditions for DIN.

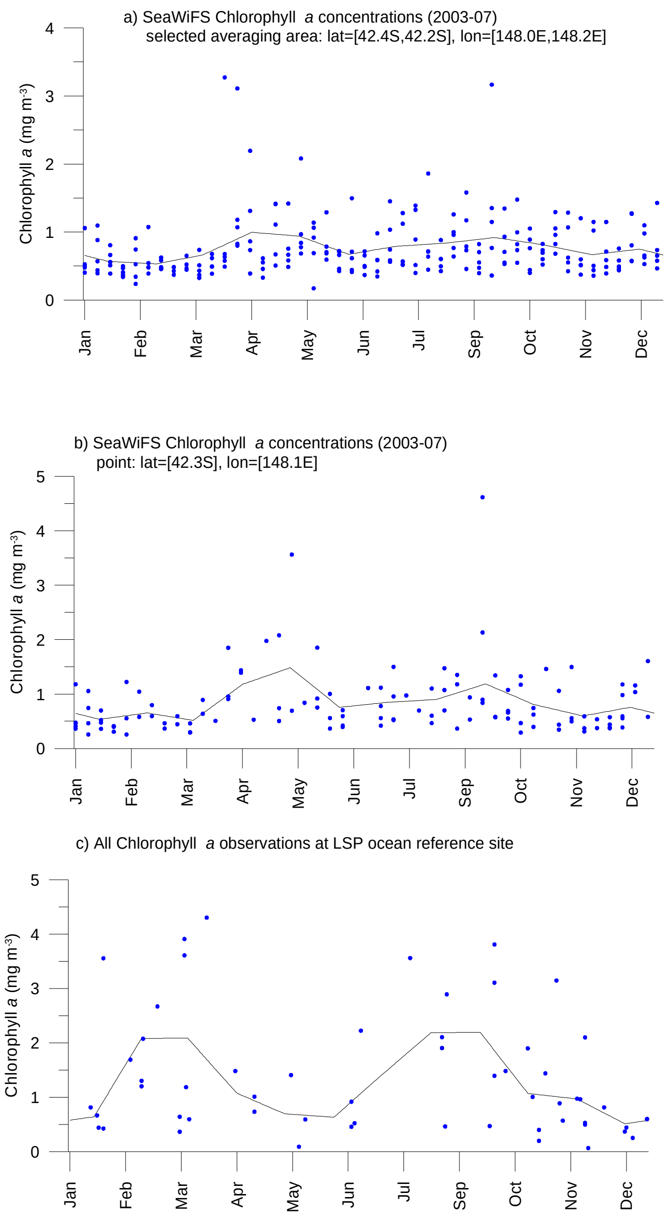


Figure 29 **Seasonal cycle of chlorophyll-*a* concentrations based on a) satellite-derived concentrations averaged over an area adjacent to the mouth of the estuary between 2003 and 2007, b) satellite-derived concentrations at a point just outside the mouth of the estuary between 2003 and 2007, and c) field measurements at the LSP ocean reference site between 1992 and 2008.**

Two data sets of chlorophyll-*a* concentrations averaged over the period 2003–07 were derived from the satellite data for sensitivity analysis: (1) concentrations measured at the closest grid cell to the mouth of the estuary (lat = [42.3°S], lon = [148.1°E]; Figure 29b); and (2) concentrations averaged over a larger area of Great Oyster Bay (lat = [42.4°S, 42.2°S], lon = [148.0°E, 148.2°E]; Figure 29a). Figure 31 compares the output of the model using constant boundary conditions for chlorophyll-*a* (as P) with each of the scenarios (solid lines). The model appears to the relatively insensitive when comparing that standard run with the satellite-derived scenarios. In contrast, the seasonal cycle derived from chlorophyll-*a* concentration measured at the ocean reference site led to increased oyster growth, elevated late summer and winter biomasses of phytoplankton and zooplankton, and a concomitant decrease in DIN concentrations during these two periods.

We also assessed how sensitive the model was to ocean boundary conditions for zooplankton (Figure 32). Although zooplankton biomass, like phytoplankton biomass, is likely to vary seasonally, no data exits to formulate a seasonal scenario, and as such constant boundary conditions for zooplankton biomass of 1, 6 and 10 mg N m^{-3} were adopted in each case. Oyster growth and phytoplankton were relatively insensitive to these changes compared with zooplankton biomass and DIN concentrations (Figure 32). This was greatest in winter when the increase in zooplankton biomass led to an increase in DIN concentrations directly due to their excretion, but also indirectly via their increase in predation on phytoplankton (Figure 32).

Finally we assessed the sensitivity of the model to changes in the DIN–river-flow relationship (Figure 5). Instead of altering the shape of the relationship we simply compared model outputs with DIN loads 20% lower and 20% higher than predicted. Even when the base river flow was increased to 25 ML per day, the model output was insensitive to these changes in the estimates of DIN loads to the estuary (Figure 33). It is worth noting that most of the forcing function sensitivity analyses were compared under a constant river flow and that under increased river flows, exchanges with the ocean, for example, will increase, potentially magnifying responses to changes in ocean boundary conditions. Interactive effects such as these will also exist for the many different combinations of parameter estimates that are possible. However, it would be impractical and difficult to interpret the outputs from all the potential permutations and combinations of parameters and forcing functions. Instead, we have chosen to vary the estimates of one or two parameters (or forcing functions) at a time to gain some basic insight into the import drivers in the model to aid model calibration.

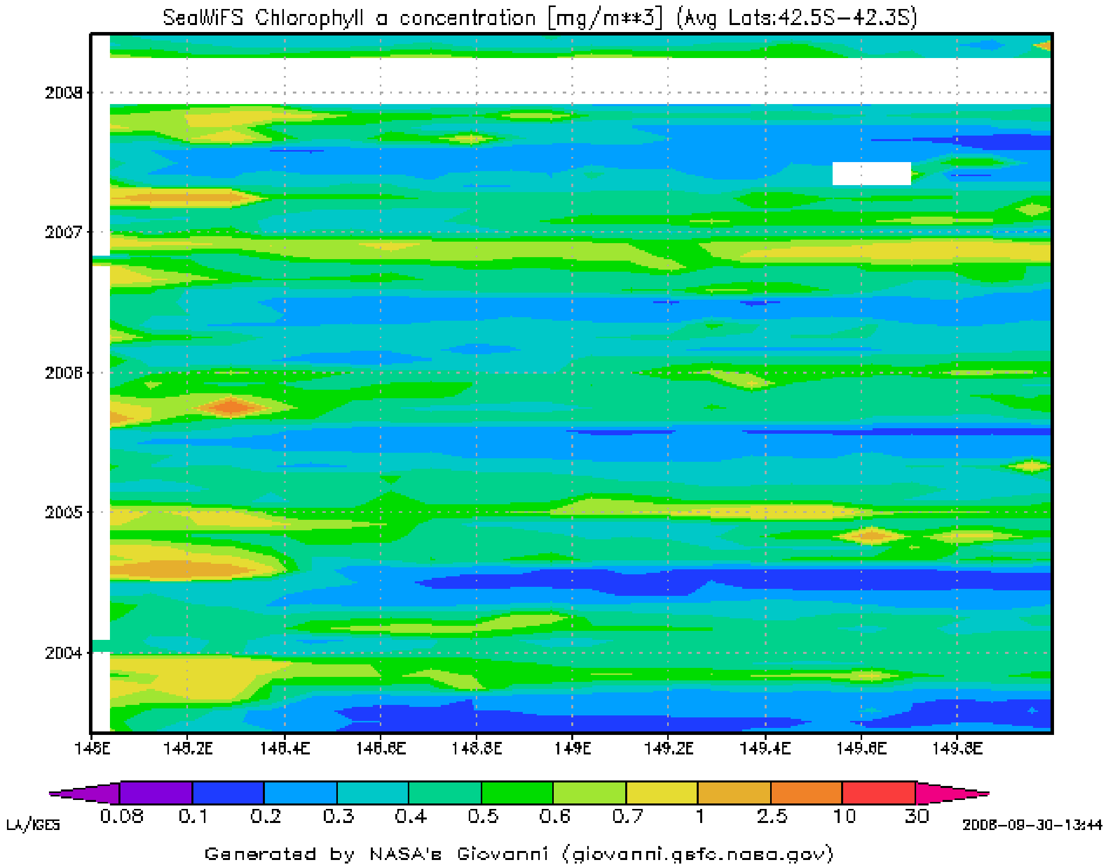


Figure 30 Time (2003–08) versus latitude (148°E to 150°E) plot of satellite-derived chlorophyll-*a* concentrations between 42.3°S and 42.5°S. The satellite chlorophyll-*a* image and data used in this study were acquired using the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

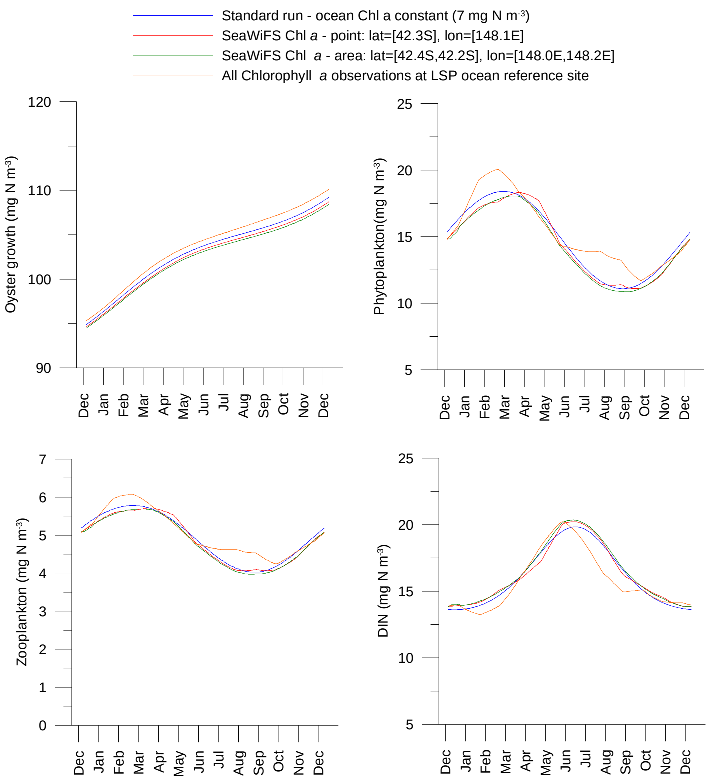


Figure 31 Comparison of model outputs for oyster growth, phytoplankton, zooplankton and dissolved inorganic nitrogen (DIN) under different oceanic boundary conditions for phytoplankton (based on chlorophyll-*a*).

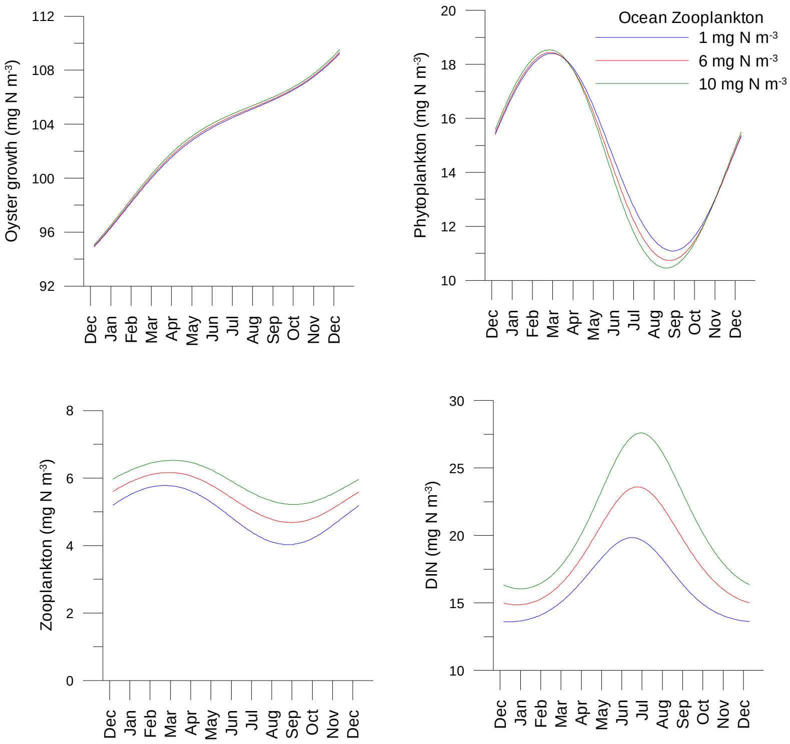


Figure 32 Comparison of model outputs for oyster growth, phytoplankton, zooplankton and dissolved inorganic nitrogen (DIN) under different oceanic boundary conditions for zooplankton.

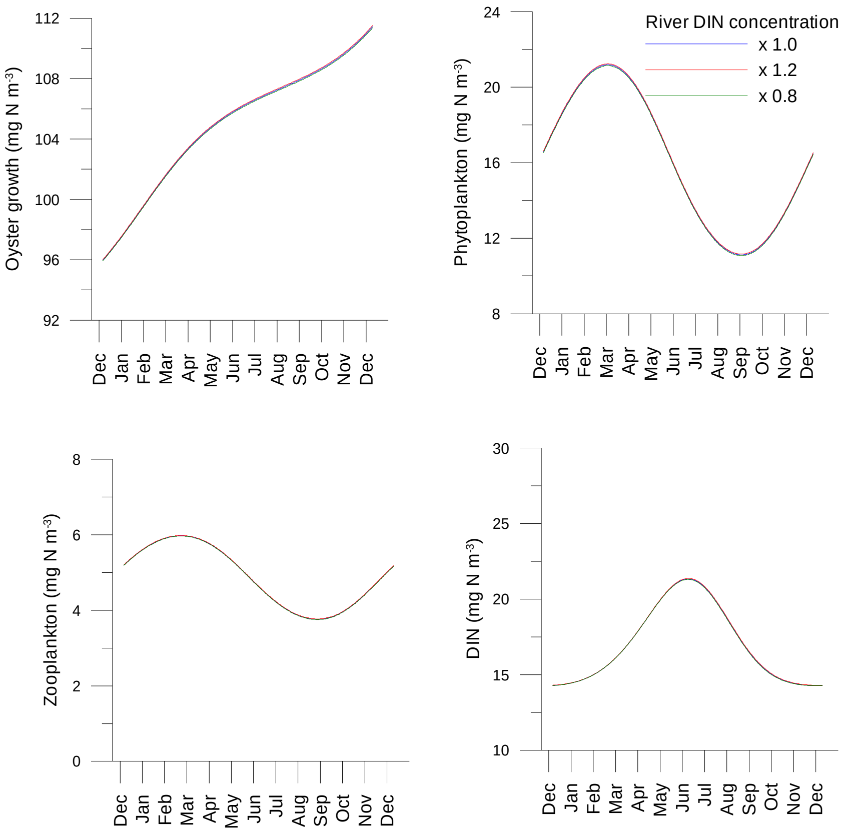


Figure 33 Comparison of model outputs for oyster growth, phytoplankton, zooplankton and dissolved inorganic nitrogen (DIN) under different river DIN concentrations.

Appendix 3D Model calibration

The model was calibrated against field data collected between the 23 January 2004 and the 23 April 2005 (Crawford et al. 2006). The model was run under idealised conditions (as defined earlier) for one year prior to the calibration period using the initial values for the state variables derived from the model spin-up described above.

Salinity measured in the field, and river flow estimated from river height data collected at DPIW's lower gauge, were used to develop the transport model as described above. A cost function was used to compare the field and model salinity, normalised by the standard deviation of the field data, to assess the fit, as per the methods of Moll (2000). The cost function is calculated as:

$$C = \frac{\sum_{t=1}^{n_t} \sum_{s=1}^{n_s} \left(M_{ts} - F_{ts}\right) / \sigma_s}{n_t n_s}$$

where M_{ts} is the value of the model at time t and site s, F_{ts} is the corresponding value of the in situ field data, σ_s is the standard deviation of the in situ field data for a particular site over time and n_t and n_s are the number of temporal and spatial data points respectively. The cost function gives an indication of the goodness of fit between the model and the field data, and the results are displayed as very good: <1 standard deviation; good: 1–2 standard deviations; reasonable: 2–5 standard deviations; and poor: >5 standard deviations.

Modelled salinity was consistent with observations during base flows and during floods (Figure 34), with a cost function (C) of 0.27 (very good). However, it was expected that salinity would have a good fit, given that this data was included in the development of the transport model. There is also very good agreement between modelled and observed DIN concentrations (Figure 35, C = 0.31). The fit for chlorophyll-*a* is also considered very good (C = 0.90); however, the model appears to overestimate chlorophyll-*a* concentrations in winter/autumn (Figure 36). The lack of chlorophyll-*a* data throughout an entire year and surrounding flood events makes interpretation and further calibration difficult.

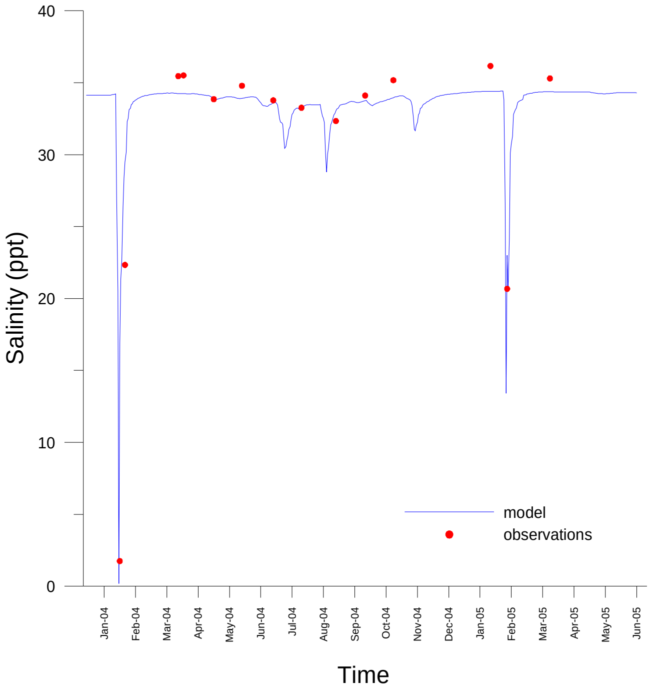


Figure 34 Comparison of modelled and observed salinity.

Due to a lack of parameters for extensive model calibration during 2004, a second calibration was carried out using the field observations collected in the first half of this study. The model was calibrated against field data collected between the 1 March 2006 and 1 July 2007. The same model spin-up procedure and initial values were used as described above. With a larger set of state variable observations to calibrate the model against in 2006–07 it is clear that the model fit was reasonably poor (Figure 37). Phytoplankton biomass was reasonably well predicted in summer, but overestimated in winter, and the average concentration of DIN was reasonably well predicted in the first 3–4 months, but was subsequently underestimated. Model fits for zooplankton and oyster growth were extremely poor, with the biomass of zooplankton overestimated and oyster growth underestimated. In general, the under representation of the seasonal variability, particularly evident for phytoplankton and zooplankton, indicates that the two forcing functions that drive seasonal patterns – temperature and light – may be having a bigger influence on the rate dependent parameters than represented in the model. It is also possible that the magnitude of seasonality in ocean boundary conditions or their influence on the estuary via estuary–ocean exchange rates (e.g. river k) may be underestimated. For oysters, it also appears that the factors that influence growth may be underestimated, namely their clearance rates, assimilation efficiency and maximum growth rate.

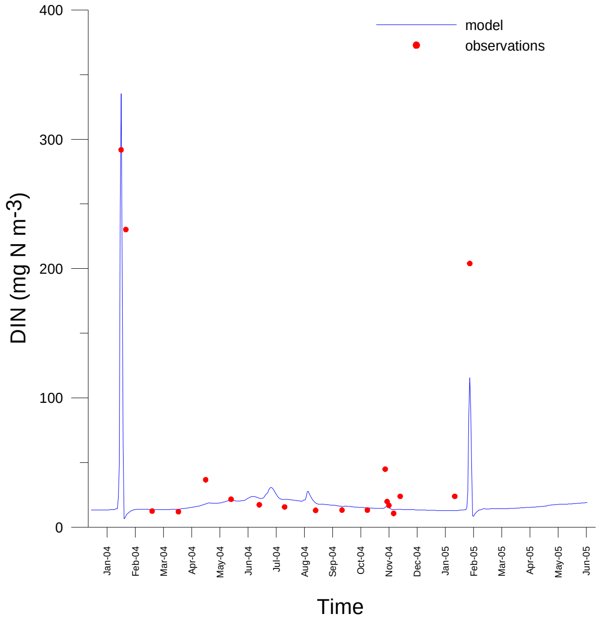


Figure 35 **Comparison of modelled and observed DIN.**

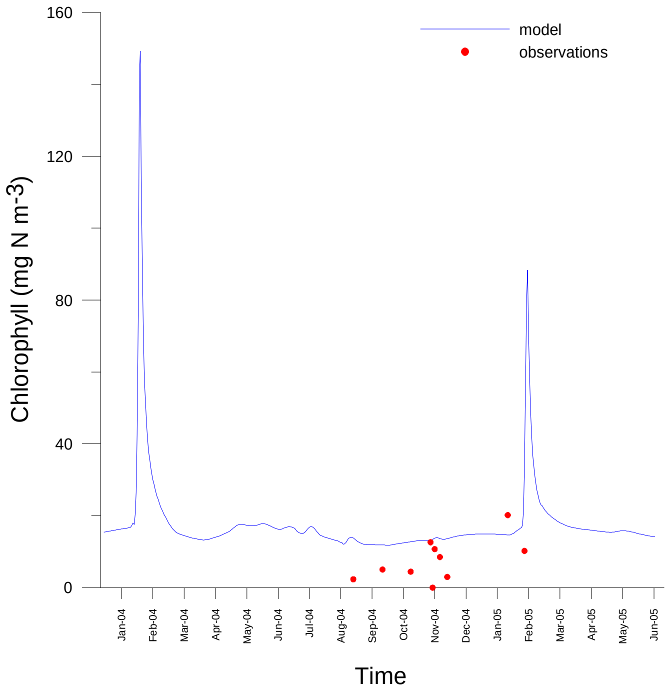


Figure 36 **Comparison of modelled and observed chlorophyll-*a* concentrations (as mg N m^{-3}).**

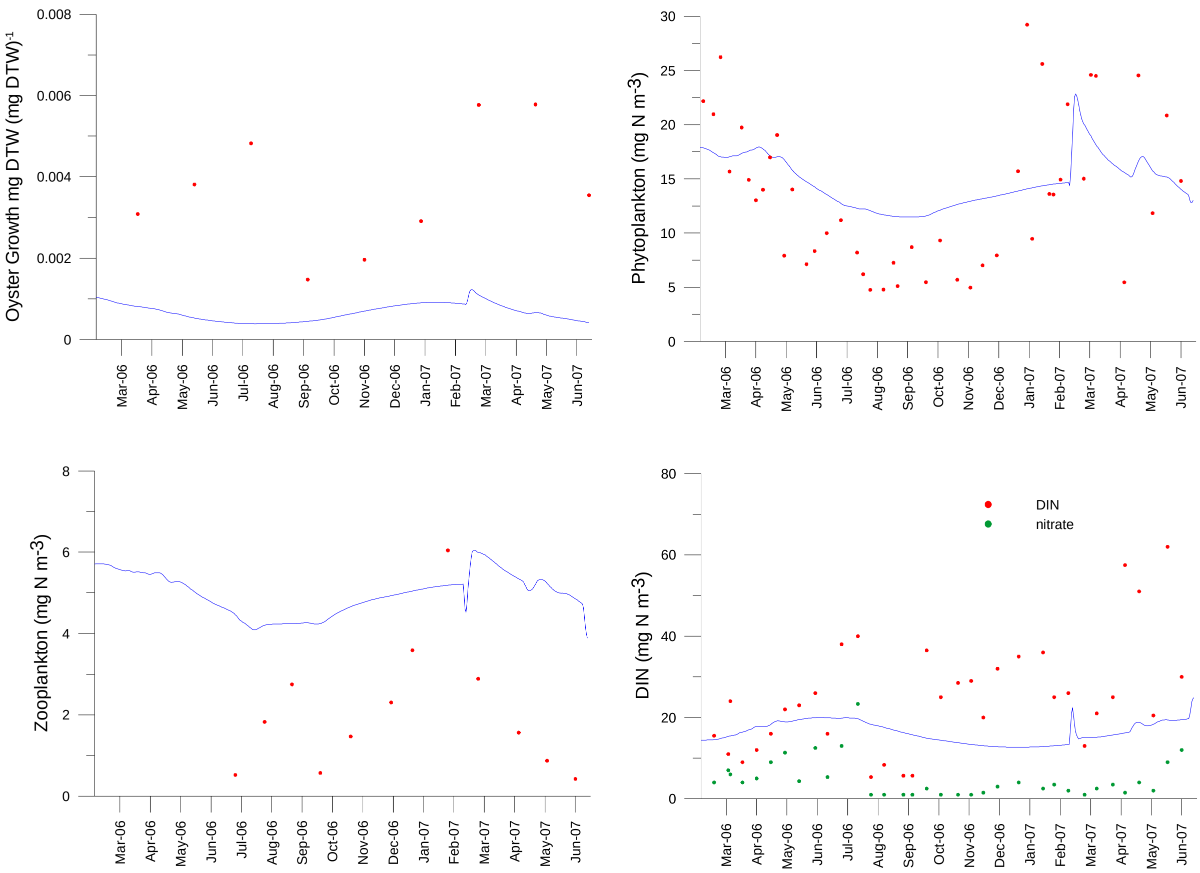


Figure 37 Comparison of modelled (lines) and observed data (points) in 2006–07 for oyster growth, phytoplankton and zooplankton biomass, and dissolved inorganic nitrogen (DIN) concentration.

To examine and understand the causes of the model performance, a sensitivity analysis was performed, beginning with the factors that influence oyster growth (e.g. clearance rate, assimilation efficiency and maximum growth rate) (Figure 38). In the standard model, the assimilation efficiency used was 0.4, based on the observations of *Crassostrea gigas* in oyster farms in Tasmania by Crawford et al. (1996); however, the range reported was 0.40–0.54. For clearance rates, 16 L g^{-1} day^{-1} (0.00015 m^3 (mg N)$^{-1}$ day^{-1}), the average recorded by Crawford et al. (1996) was used in the standard model; however, clearance rates up to 40 L g^{-1} day^{-1} (0.00037 m^3 (mg N)$^{-1}$ day^{-1}) were also observed in Tasmania, and Raillard & Ménesguen (1994) report a maximum value of 48 L g^{-1} day^{-1} (0.0005 m^3 (mg N)$^{-1}$ day^{-1}) for oysters overseas. Similarly, maximum growth rates beyond the value used in the standard model have also been recorded locally (Crawford et al. 1996; this study). Figure 38 demonstrates that an increase in any one of these parameters will help close the gap between the model output and the observed oyster growth rates. Rather than using a value at the extremes of the ranges reported in the literature, an increase in each of the parameters in combination within the ranges reported in the literature seemed most appropriate (see Figure 38d).

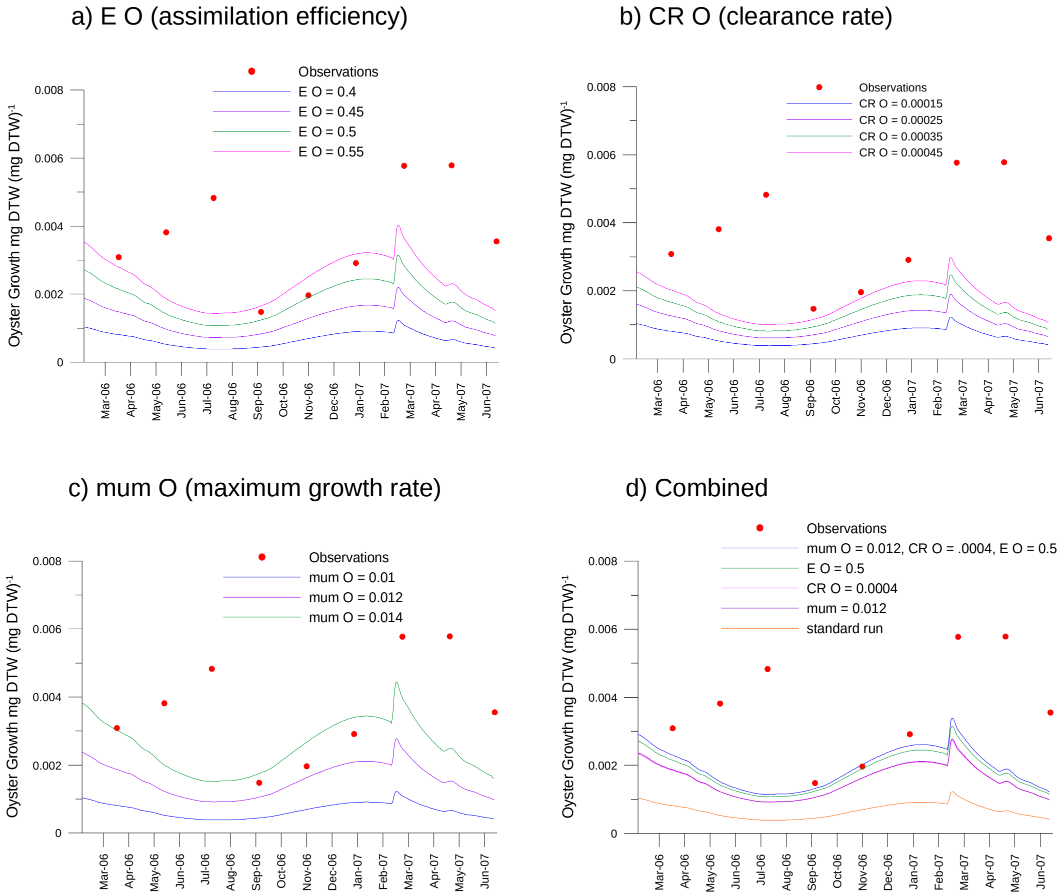


Figure 38 Comparison of modelled (lines) and observed oyster growth (points) using different oyster feeding parameters for a) assimilation efficiency (E O), b) clearance rate (CR O), maximum growth rate (mum O), and d) a combination of changes to all three parameters.

In order to increase the magnitude of the seasonal cycles in the model in line with field observations, the effects of an increased dependence of the rate parameters on temperature was examined by increasing Q10 (Figure 39). The effect of increasing Q10 was clearly evident (Figure 39), and as such, the value was changed from 1.8 in the standard run to 2.7.which is within the range (1–4) reported in the literature (see Murray & Parslow 1999). For the other parameters and forcing functions that may alter the magnitude of seasonal variation (light saturation intensity and boundary conditions), the effects on the model outputs were negligible. When using the alternative boundary conditions for DIN discussed above, seasonal variability decreased rather then increased in the model output. Although the effect of using the SeaWiFs chlorophyll-*a* data for parameterising the boundary conditions for phytoplankton had a negligible effect on the model outputs, it was used instead of the constant 7 mg N m^{-3} of ocean P in subsequent model runs because it provides more realistic boundary conditions.

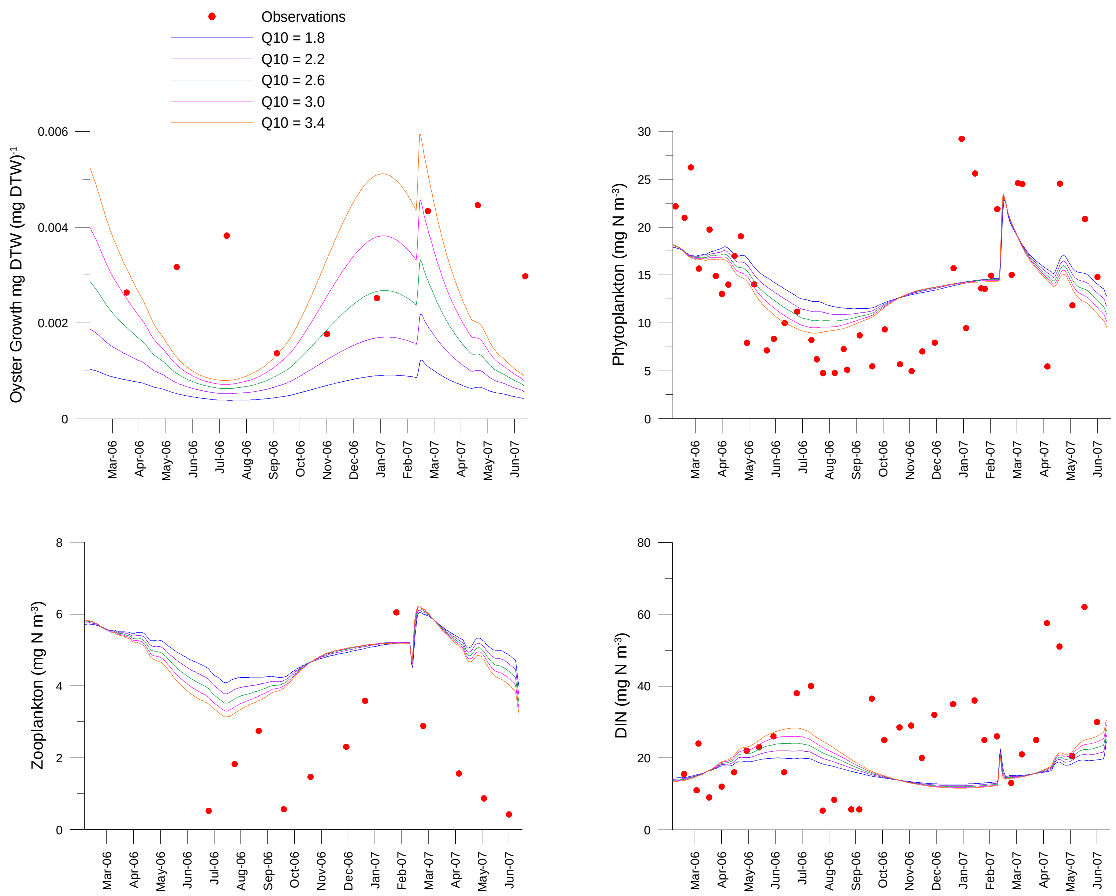


Figure 39 Comparison of observations (points) and model outputs (lines) with varying degrees of temperature dependence (i.e. via the Q10 value).

To decrease the biomass of zooplankton predicted by the model, an increase in the quadratic mortality term (mQ Z) and a decrease in the zooplankton assimilation efficiency (E Z) were examined. Not surprisingly, zooplankton biomass decreased for both of these parameter changes (Figure 40). The change in E Z rather than mQ Z was retained for subsequent model runs because the model fit for phytoplankton biomass and DIN concentration was better when changing E Z.

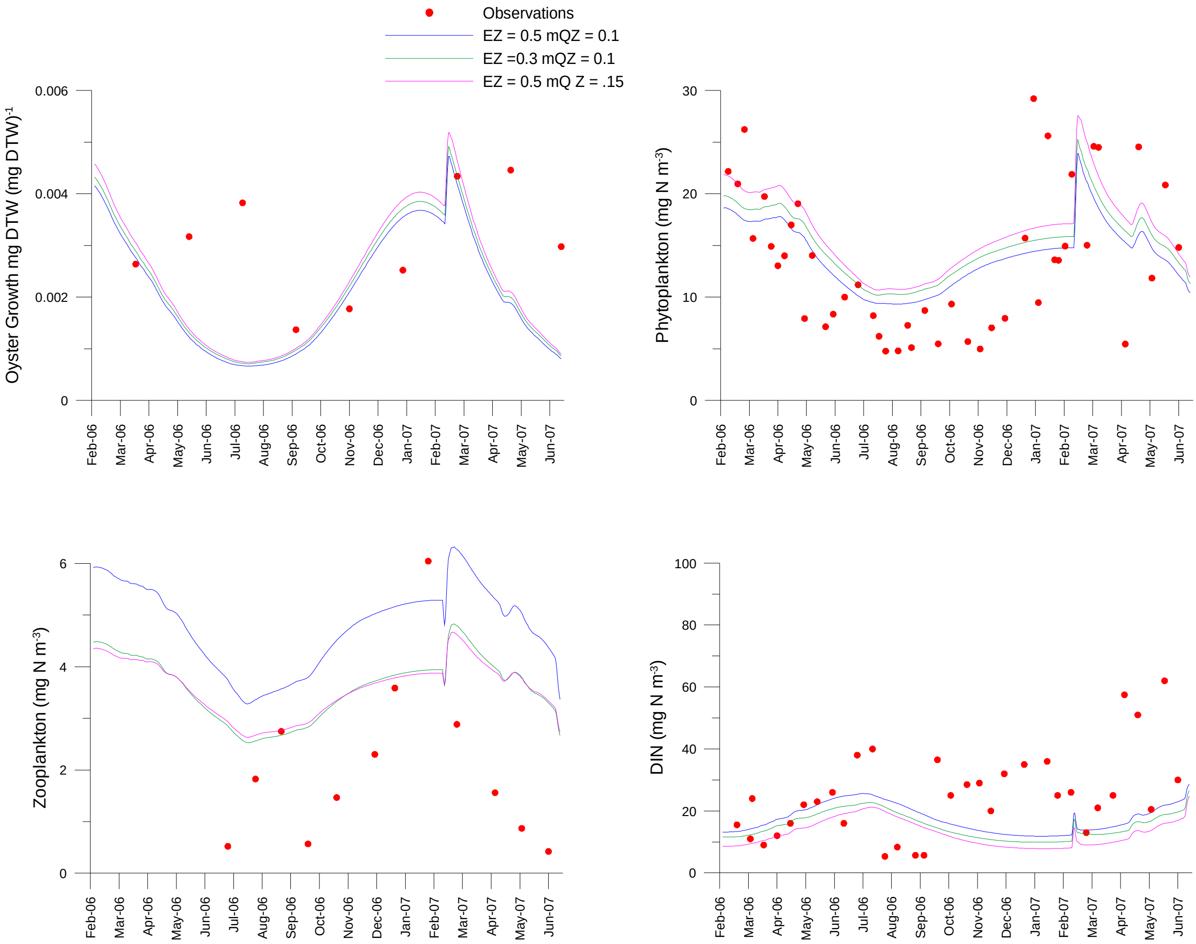


Figure 40 Comparison of observations (points) and model outputs (lines) with a different zooplankton assimilation efficiency (E Z) or quadratic mortality term (mQ Z).

In order to decrease the biomass of phytoplankton but increase the concentration of DIN in the water column, the sinking rate of phytoplankton was increased from 0.3 to 0.45 (Figure 41). At the same time, the river constant k, which determines exchange volume at zero river flow, was increased from 1 to 6 to improve the model fit. Finally, to further improve the model fit for zooplankton, the ocean boundary biomass of zooplankton was changed from 2 to 1 mg N m^{-3}, and the rate of breakdown for dissolved organic nitrogen was increased from 0.0176 to 0.025 to improve the model fit for DIN (Figure 42).

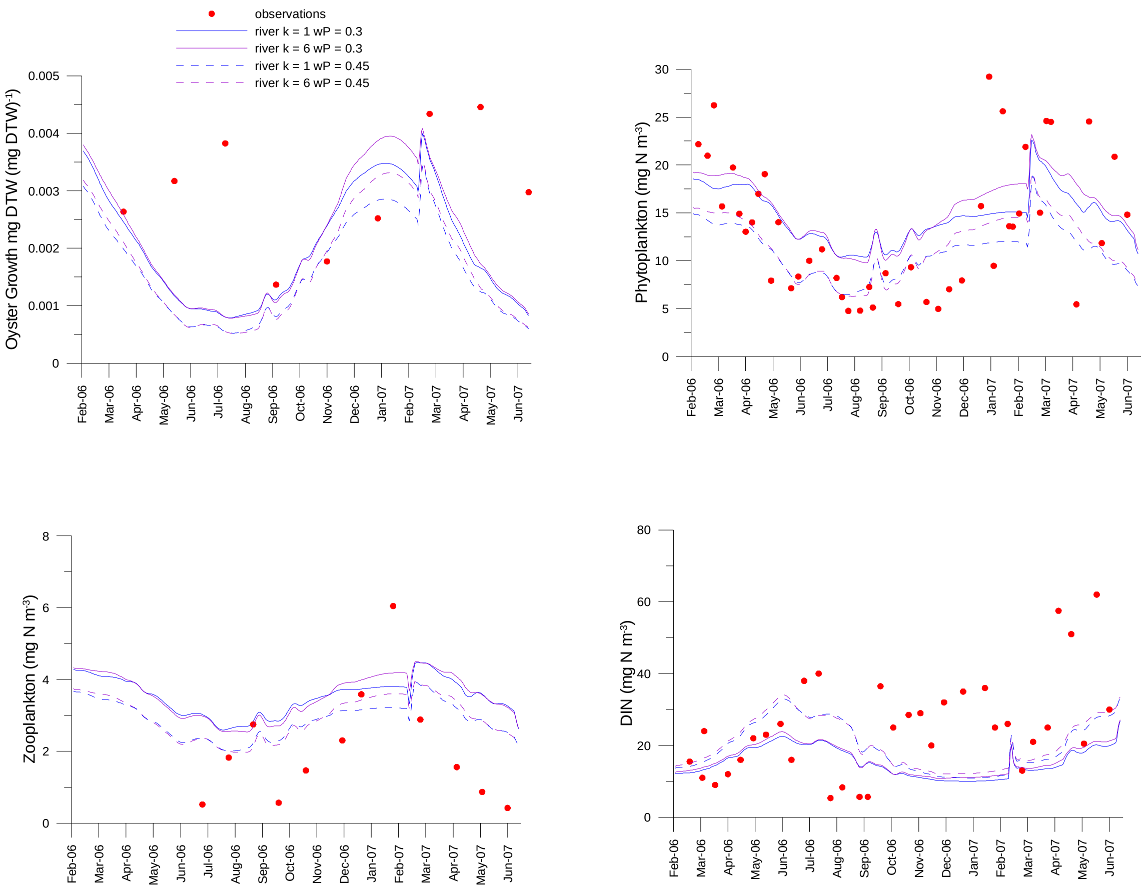


Figure 41 Comparison of field observations (points) and model outputs (lines) with different phytoplankton sinking rates (wP) and ocean exchange volume at zero river flow (determined via constant river k).

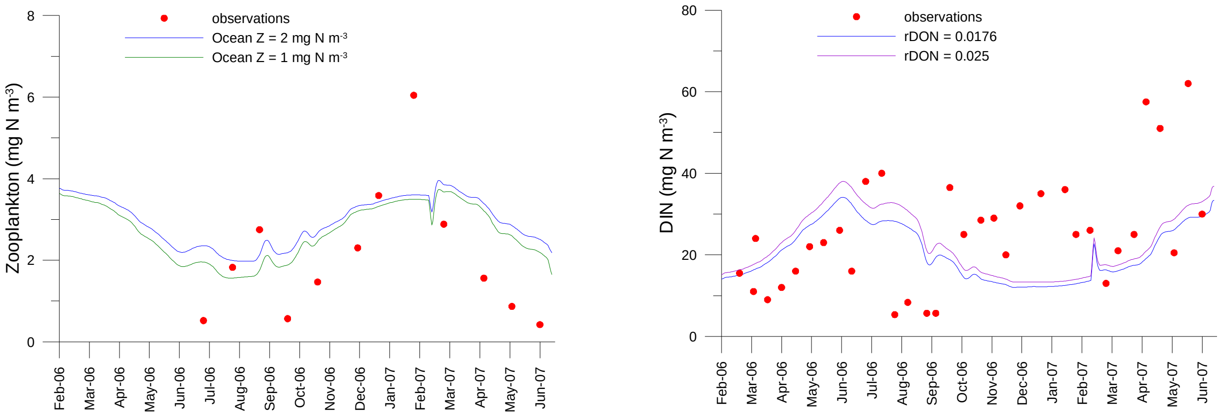


Figure 42 Comparison of observations (points) and model outputs (lines) for zooplankton and DIN in the water column with a different ocean boundary biomass for zooplankton (Ocean Z) and breakdown rate for DON in the water column (rDON) respectively.