INFORMD2

Risk-based tools supporting consultation, planning and adaptive management for aquaculture and other multiple-uses of the coastal waters of southern Tasmania

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April 2017

FRDC Project No **2012/024**

ISBN 978-1-4863-0842-2

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2017

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Acknowledgments

This project was funded by the Fisheries Research and Development Corporation (FRDC), CSIRO, and the University of Tasmania.

The authors would like to thank to Graham Woods (Tasmanian Department of Primary Industries, Parks, Water and Environment: Marine Farming Branch); Adam Main (Tasmanian Salmon Growers Association); Dom O'Brien and David Whyte (Huon Aquaculture); Matt Barrenger and Linda Sams (Tassal); Tom Lewis (Oysters Tasmania) Kevin Ellard (Tasmanian Department of Primary Industries, Parks, Water and Environment: Animal Biosecurity and Welfare) for critical data, advice and feedback over the course of the INFORMD2 project.

Our thanks also to John Parslow and Keith Sainsbury for their roles in supporting the initial proposal development for INFORMD2; to Maree Fudge (RDS Partners) and Laura Smith and Roslyn Asten (IMAS) for assisting with the Your Marine Values component of the study; to Mike Herzfeld, Farhan Rizwi and John Andrewartha (CSIRO) for making hydrodynamic model outputs available to the study; and to Emlyn Jones (CSIRO) and Raymond Williams (University of Tasmania) for advice relating to flow states in the estuarine system.

Abbreviations

BGC	Biogeochemical
BEMP	Broadscale Environmental Monitoring Program
CIA	Cumulative Impact Assessment
CONNIE	CONNectivity InterfacE
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DHD	Derwent-Huon-D'Entrecasteaux
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DPIPWE	Department of Primary Industries, Parks, Water and Environment
DST	Decision Support Tool
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Authority (Tasmania)
IMAS	Institute of Marine and Antarctic Studies (University of Tasmania)
INFORMD	Inshore Network for Observation and Regional Management Derwent-Huon
MAREE	MARine Ecological Emulator
ODE	Ordinary Differential Equation
POMS	Pacific Oyster Mortality Syndrome
SLO	Social License to Operate
SOM	Self-Organising Map
TSGA	Tasmanian Salmon Growers Association
VMS	Virtual Monitoring Site
WSS	Willmott skill score
YMV	Your Marine Values (a component of the INFORMD2 study)

Executive Summary

Background

Salmon aquaculture is a major component of the Tasmanian economy (currently $700 million with plans to expand to $1 billion by 2030). However, the industry operates along a populated coastline in waterways shared with a range of other industrial and recreation uses. Both government and industry recognise that maintaining high environmental standards is not only critical to the husbandry of fish stocks, but also to maintaining a social license to operate in Tasmania. This is underlined by the 2015 Senate Inquiry into the salmon industry and recent changes to the regulatory framework that reflect the current size and maturity of the industry.

Scientific understanding of the marine system clearly has a central role in maintaining community confidence in the environmental sustainability of the industry. However, this understanding must be both relevant to stakeholder values and accessible in a form that effectively supports planning and management. INFORMD2 directly addressed these needs by identifying stakeholder values and developing technologies that provide timely and relevant information to government industry and the community. This was a major collaborative study between scientists at the CSIRO and the University of Tasmania with involvement of the Tasmanian Government through the Department of Primary Industries, Parks, Water and Environment, and the Tasmanian aquaculture industry through the Tasmanian Salmon Growers Association, Huon Aquaculture, Tassal, and Oysters Tasmania.

Aims and scope

INFORMD2 had an ambitious agenda aimed at supporting environmentally sustainable development of the Tasmanian salmon industry in southern Tasmania and helping to establish a broader social license for that development. This was achieved by developing four new products to assist in planning and ongoing management of aquaculture leases:

(i) A new approach to identifying community, government and industry values (Your Marines Values – YMV) that has facilitated a more informed engagement processes and greater trust between participants.

(ii) A new biogeochemical model for the waters of the Derwent Estuary, Huon River and D'Entrecasteaux Channel. This model has been validated in detail and is now being used by stakeholders to test scenarios for planning and water quality impact assessment.

(iii) A publicly accessible online decision support tool (CONNIE) that can be used to identify waterborne interactions between aquaculture and other marine activities and assets. This facility is now being used extensively to identify impact zones and quantify pathogen risks.

(iv) A new online decision support tool (MAREE) to be used by government and industry for rapid assessment of the impacts of marine and coastal activities on local water quality. Examples include the impacts of nutrient and sediment loads associated with stocking of salmon leases; sewage treatment plants, other industrial discharges; and altered land-use in local catchments.

These models and tools integrate a diverse body of information and understanding relating to the marine environment of southern Tasmania. Together with ongoing monitoring programs, they are helping to place southern Tasmania as a global leader in environmental management of aquaculture.

Methodology and results

The "Your Marine Values" (YMV) component of the study commenced in 2012 with the aim of identifying what Tasmanians (local communities, marine industries and managing agencies) value most about the marine waters of southern Tasmania, with a specific focus on those marine values affected by and affecting aquaculture activity. Characterising public values involved a rigorous and highly participatory social science research program, including a series of individual stakeholder workshops in regional locations, an online survey, and a cross-sector workshop involving management agencies, researchers, aquaculture and commercial fisheries industry representatives and community representatives. The level of community engagement was overwhelming and as a consequence a broad ranging suite of ecological, social and economic values were identified. The findings provided an opportunity to communicate these values to the broader Tasmanian community and have facilitated a more informed engagement process, and greater trust between participants. They also provided guidance on the capabilities that were needed to be incorporated into the risk-based decision support tools described below.

Development of a regional biogeochemical model provided a vehicle for exploring future scenarios and testing management strategies, particularly in addressing long-term system-wide changes. This model combined hydrodynamic flows with sediments, nutrients, phytoplankton and zooplankton in various forms. It has been use to derive nutrient budgets for the system that incorporate inputs from catchments, aquaculture and sewage treatment plants. Scenario modelling based on past, recent and future nutrient loads has also provided key inputs for the development of the decision support tools described below.

The spatial connectivity tool CONNIE provides estimates of the dispersal of any contaminant (e.g. nutrients, sediments, oil, debris) through the marine system of southern Tasmania. It combines currents generated in near-real-time by a hydrodynamic model of the region with particle tracking techniques to make statistical estimates of exposure risk throughout the waterways. Importantly, the tool is freely available online (www.csiro.au/connie/) and requires minimal training. It is already finding a range of practical applications including identifying impact zones around salmon leases from dispersal of fish faeces and biofouling; assessing risks to abalone grounds at the southern end of the D'Entrecasteaux Channel; and identifying risks of Pacific Oyster Mortality Syndrome (POMS) infecting new leases during the first ever Tasmanian outbreak in early 2016.

The online tool MAREE provides a rapid assessment of the impacts of new coastal and marine activities on local water quality without the need to run the regional biogeochemical model. MAREE was developed by combining information on exposure from CONNIE with simplified approximations of biogeochemical transformations from the biogeochemical model. While outputs contain limited spatial and temporal information (compared to the biogeochemical model) they are specifically targeted at the needs of managers and can be generated online by non-expert users.

Implications for stakeholders

INFORMD2 represents a major advance in our capabilities to assess the risks associated with new activities and developments in the southern Tasmanian marine environment. Importantly, these tools not only improve the effectiveness of these assessments, but also the efficiency with which they can be carried out. This is of particular value where industries or regulators need to undertake a preliminary assessment as part of screening or staged approval processes.

The INFORMD2 risk-based management tools can also help to reduce the potential for conflict between users of the marine system. For example, many conflicts are based around perceived risks and the ability to address concerns quickly and cheaply with online tools will allow managers to focus on issues posing significant and quantifiable risks.

Recommendations

INFORMD2 has developed a range of methods and tools, and demonstrated their utility in the context of aquaculture and other coastal and marine activities in the Derwent, Huon and D'Entrecasteaux Channel region. However, expansion of salmon aquaculture is now focused in the neighbouring Storm Bay region. While CONNIE includes Storm Bay and is already supporting planning for this region, the geographical coverage of the biogeochemical model and MAREE are more restricted. The need to extend these models into Storm Bay is now urgent if planning and implementation of new leases and associated monitoring is to be supported at a similar level to the Huon and Channel. Expansion of these technologies into Storm Bay would also provide an opportunity to establish biogeochemical modelling as a near-real time service integrated with observational data streams.

The INFORMD2 technologies would similarly benefit management of aquaculture along the Tasmanian East Coast and within the Macquarie Harbour on the west coast. Here the decision support tools could be tailored to provide stronger focus on major issues such as harmful algal blooms or dissolved oxygen dynamics.

Keywords

Atlantic salmon; *Salmo salar*; aquaculture; risk-based; decision support tools; marine values; dispersal; connectivity; biogeochemistry; Derwent Estuary; Huon Estuary; D'Entrecasteaux Channel; Storm Bay

1. Introduction

Major limitations have been identified in existing approaches to managing environmental risks (Dalmer 2012). Specifically, traditional Environmental Impact Assessments (EIA) entail site-specific project-by-project reviews, which are assumed to be additive in their cumulative effects. Dalmer (2012) argued that the next generation of Cumulative Impact Assessments (CIA) need to move beyond the additive approach to address cumulative, nonlinear and threshold effects, ecological interactions (synergistic or antagonistic), and be undertaken at regional scales more relevant to spatially-explicit ecological processes. Furthermore, to increase their relevance and uptake, assessments will need to address interconnected social, economic and environmental issues and incorporate "what if" future scenario analyses in order to assess the sustainability of risk management options. The INFORMD2 project has developed Decision Support Tools to address all these issues in the context of aquaculture and other marine uses in southern Tasmania.

While the value of Australian aquaculture has increased only modestly over the past decade, significant declines in tuna and pearl oyster have been more than offset by a major expansion in the value of Tasmanian salmon aquaculture (Figure 1.1). A large proportion of the salmon production is concentrated in the Huon River and D'Entrecasteaux Channel (Figure 1.2). Salmon farmers and the Tasmanian Government have aspirations for continued sustainable expansion of the industry, which will require broad community support. A 2015 Senate inquiry into the Tasmanian salmon industry recommended that the Tasmanian Government make environmental information and data relating to the industry more openly available. The INFORMD2 project was designed to generate and make accessible key environmental information that will support evidence-based decisions.

INFORMD2 was a 4-year FRDC-funded project (2012-2016) undertaken by the CSIRO and the University of Tasmania. It built on a long-term collaborative research program conducted under the partnership INFORMD (Inshore Network for Observation and Regional Management of the Derwent-Huon). The project consultative group included key representatives of the Tasmanian State Government (DPIPWE), the salmon farming industry (Tassal and Huon Aquaculture), Tasmanian Salmon Growers Association (TSGA), and the oyster industry (Oysters Tasmania). Their involvement ensured that the outcomes reflected both the broader regulatory and planning issues, as well as addressing issues specific to the aquaculture industry. The project has also engaged with the broader community through a series of workshops and links with organisations such as the Derwent Estuary Program and The D'Entrecasteaux and Huon Collaboration.

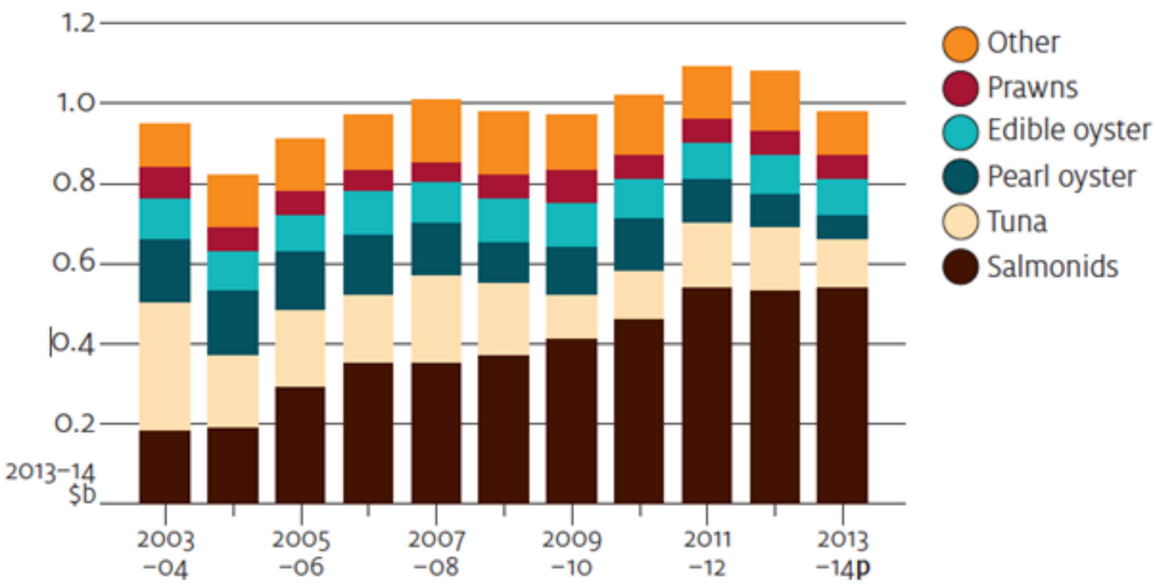


Figure 1.1: Real value of Australian aquaculture production ($billion) over the financial years 2003-04 to 2013-14 (Australian Bureau of Agricultural and Resource Economics and Sciences 2015).

The focus of INFORMD2 was on developing practical tools to support planning and management of aquaculture and other coastal and marine activities within a CIA framework (see Appendix C for a list of project objectives and related outcomes). A diverse range of approaches have been used in producing a framework for understanding stakeholder values known as Your Marine Values (YMV); a detailed water quality model that captured the key physical and biogeochemical processes in the system; and two online Decision Support Tools (DSTs) providing critical information on dispersal and connectivity in the system and the impacts of new activities and facilities on local water quality. The decision support tools have been designed to provide immediate and relevant information to non-expert users and hence may have the potential to support significant improvements in the efficiency and effectiveness of environmental management in southern Tasmania.

Figure 1.2: Map of the Derwent Estuary, Huon Estuary, D'Entrecasteaux Channel and surrounding catchments in southeast Tasmania. The inset shows existing aquaculture leases in the south.

2. Objectives

INFORMD2 was designed to assist industry, regulators and local communities to gain a common understanding of the potential impacts of existing and proposed developments on stakeholder values in the coastal waters of southern Tasmania. A transparent and accessible online decision support system will help identify strategies that balance opportunities and risks across sectors, thereby providing all stakeholders with confidence in the sustainability of operations. While the initial focus was on planning and management of aquaculture development, the support system will have much broader application and benefit multiple sectors over the longer term.

The objectives of the project as identified in the original proposal were:

i. In relation to aquaculture and the marine environment of southern Tasmania, characterise key economic, social and environmental values and aspirations from industry, government and community perspectives.

ii. Relate these values qualitatively to measurable indicators based on an understanding of key biophysical and socio-economic processes.

iii. Develop a framework to support spatial risk assessment for planning of future development within the context of other natural processes and anthropogenic activities within the system, with an initial focus on aquaculture leases.

iv. Develop a framework for developing and evaluating spatial risk management strategies, with an initial focus on managing within and across aquaculture leases

v. Integrate the planning framework (objective iii) and risk management framework (objective iv) into an online tool accessible to stakeholders.

These objectives did not change over the duration of the project.

3. Method

A number of complementary, consistent and interconnected products and tools were developed in the project, all aimed at supporting management of the southern Tasmanian marine environment (Figure 3.1):

i. Identification of key marine values held by local communities, industry and government (*YMV*).

ii. An improved regional biogeochemical model for estimating water and sediment quality.

iii. An online decision support tool (*CONNIE*) for exploring dispersal and spatial connectivity of substances (e.g. contaminants) and organisms (e.g. pathogens).

iv. An online decision support tool (*MAREE*) for exploring the impacts of changed management or new developments on local water quality.

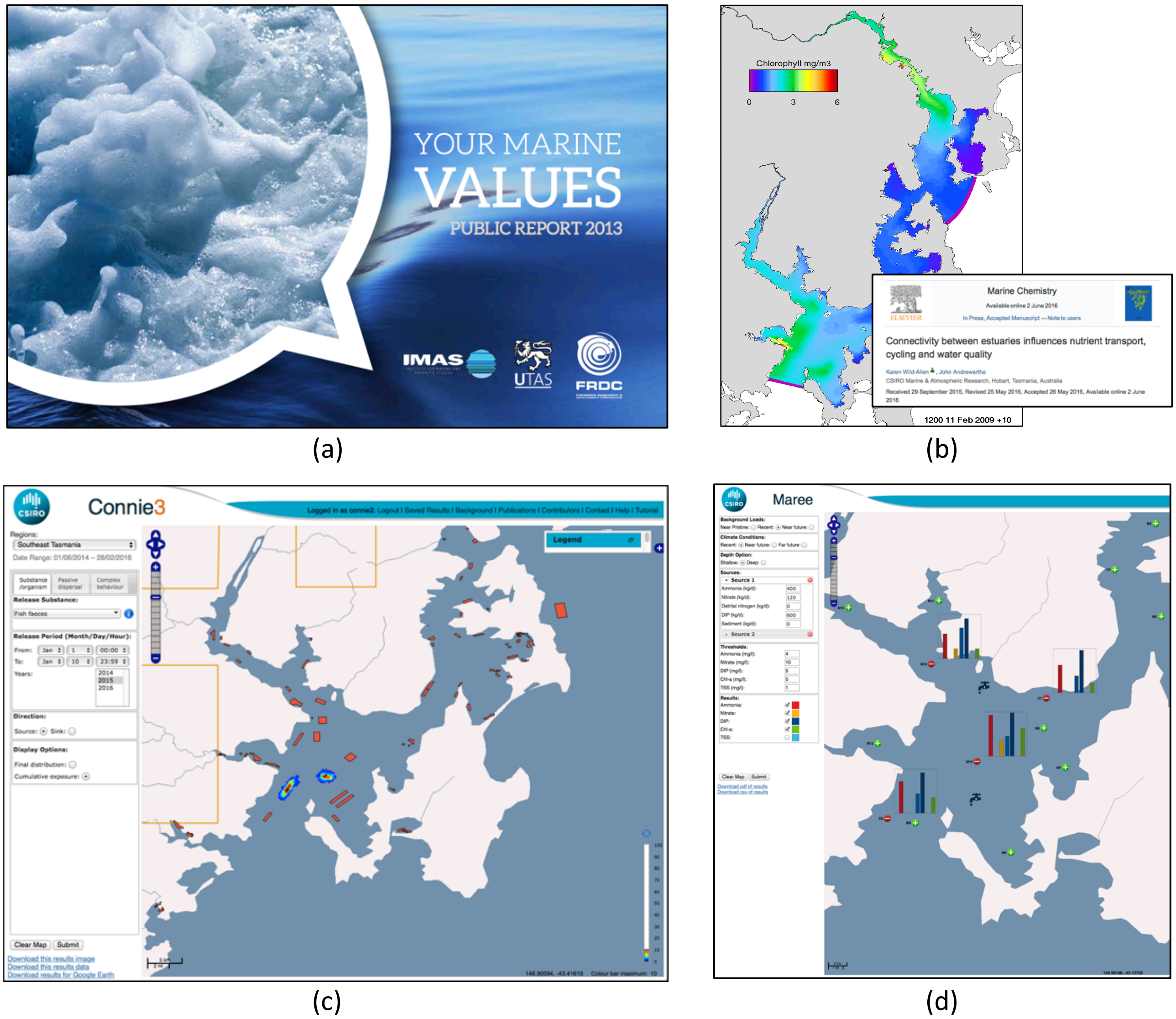


Figure 3.1: Summary of outputs from INFORMD2. (a) The YMV public report (Ogier and Macleod 2013). (b) The regional biogeochemical model. (c) The online CONNIE tool for exploring dispersal, exposure and connectivity. (d) The online MAREE tool for exploring the effects of coastal and marine activities on water quality under current and future conditions.

The marine values identified in (i) guided the design of the biophysical models and decision support tools listed in (ii-iv) in terms of the outputs and outcomes they were required to generate. The models themselves were also strongly interdependent (Figure 3.2). A summary of what each of the project products does and how they might be used in an assessment context is provided in Table 3.1.

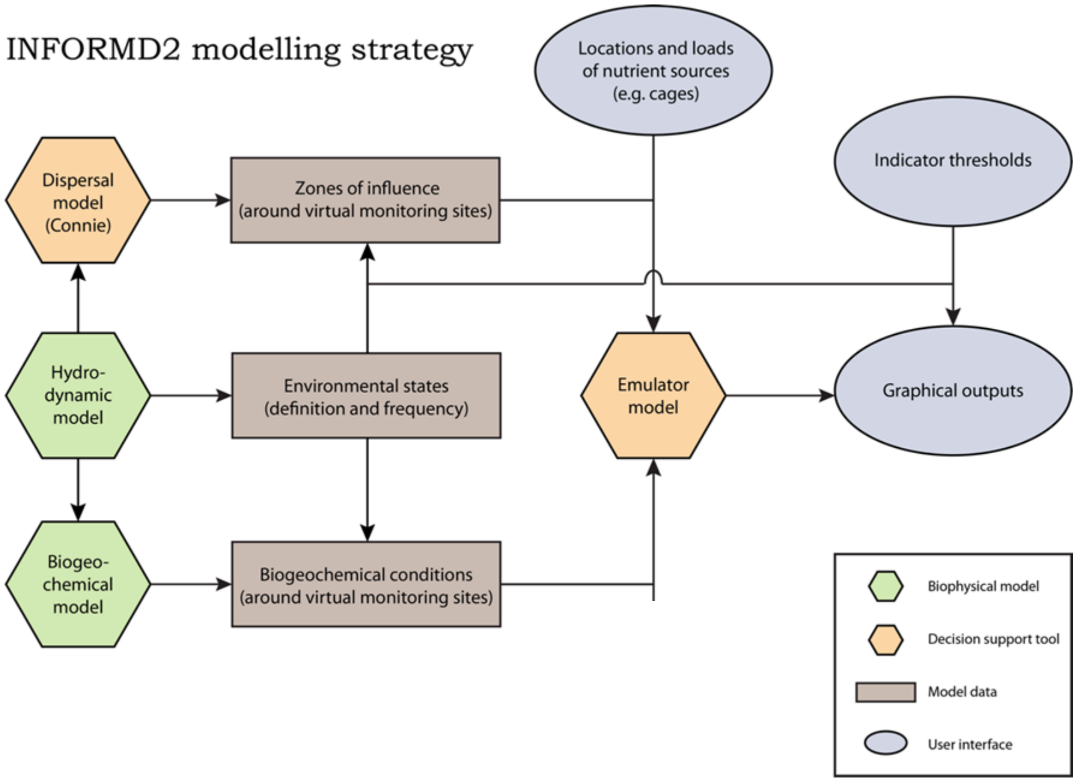


Figure 3.2: Links between the biophysical models and risk-based decision support tools developed within the INFORMD2 project. Arrows indicate flow of information. In the future, as new information is incorporated into the underlying biophysical models, these improvements can be propagated through to the decision support tools.

Table 3.1: Tools developed within the INFORMD2 project with brief statements of what they do and when they might typically be used in environmental assessment processes.

Framework, model or decision support tool	What it does	When to use it within the assessment process
YMV Framework	Provides a framework to help identify how changes in management or new developments can potentially impact on the values of other stakeholders in the system.	Preliminary assessments of changes in management or new developments to identify potential sources of conflict among stakeholders.
BGC model	Offline calculations of the biogeochemical response of the system to changes in climate conditions or anthropogenic loads of nutrient and sediments.	Exploring impacts of changes that could potentially transform the state of the system or when detailed spatial and temporal information is required.
CONNIE DST	Rapid online calculation of waterborne dispersal and exposure for a wide range of substances and organisms.	Useful for both preliminary assessments and more comprehensive assessment processes.
MAREE DST	Rapid online calculation of local changes in water quality in response to new sources of nutrients and sediments.	Useful for both preliminary assessments and as part of more comprehensive assessment processes.

3.1 Understanding the marine values held by stakeholder groups

An effective mechanism for communication between groups with a stake in the marine environment (community, industry and government) is critical to ensure that industry development is based on shared understanding that can be used as a basis for resolving potential conflicts. The YMV component of the study commenced in 2012 with the aim of identifying what Tasmanians (local communities, marine industries and managing agencies) value most about the marine waters of the southern Huon and D'Entrecasteaux Channel in South East Tasmania, with a specific focus on those marine values affected by and affecting aquaculture activity.

Characterising public values involved a rigorous and highly participatory social science research program. This included a series of individual stakeholder workshops in regional locations; an alternative online survey; and a cross sector workshop involving management agencies, researchers, aquaculture and commercial fisheries industry representatives and community representatives. The level of community engagement was very high with a total of 137 responses (Table 3.2). As a consequence, a broad range of ecological, social and economic values were identified.

The YMV study not only identified individual stakeholder values, but also characterized those values shared by government, the aquaculture industry and community stakeholders and linked them to specific governing legislation and policy (both regulatory and operational); relevant research and monitoring; and measurable indicators which provide information on the condition of those values (Ogier and Macleod 2013). The findings also provided an opportunity to communicate these values to the broader Tasmanian community and to highlight the critical links between those values, science and governance structures. Stakeholders have proposed that the key marine values identified be used as the reference point for further evaluating the status of the D'Entrecasteaux Channel marine system and for facilitating future discussions between stakeholders.

Table 3.2: Age ranges and interests nominated by workshop and survey respondents.

Respondent characteristic	Category	Number of respondents
Age of respondents	Unspecified	2
	18-29	7
	30-49	40
	50-69	76
	70+	12
	Total	137
Interests of respondents	Local resident	103
	Recreational user	89
	Aquaculture industry	13
	Other marine industry	16
	Government	1
	Local business	11
	Other	20

Linking values

In addition to improving communication and trust between stakeholders, YMV also provided a basis for selecting elements to be included within DSTs. This approach clearly defined the range of values the DSTs needed to support and thereby the structural elements required for modelling. The first step involved identifying interactions between the 17 identified values in terms of the ecological processes and human activities that are significant at the estuary/channel scale. Values that were closely aligned and interacted with other values in similar ways were grouped so as to remove any redundancy in the matrix of interactions. The groups were also represented in the form of a digraph of interactions and both representations were used to validate identified interactions at stakeholder workshops.

Using an approach referred to as loop analysis (Levins 1974, http://ipmnet.org/loop/default.aspx), the digraph of interactions was mathematically analysed to determine the qualitative responses to changes in the state of any of the values. This included determining the linear stability of the system, its predictability, and its qualitative response (increase, decrease, or neutral) to a sustained perturbation to any of the system components (assuming that the system remains near equilibrium and does not transition to a new state).

The loop analysis did not explicitly include Tasmanian Aboriginal values as a separate category only because the level of consultation required to validate the interactions was beyond the scope of the current study. It will be an important aspect to include in future assessments.

3.2 Biogeochemical (BGC) modelling

Biogeochemical modelling provided detailed information on water quality parameters such as nutrients sediments and dissolved oxygen. Once calibrated, it could also be used to extrapolate sparse observational data and improve our understanding of the processes influencing water quality over large areas. In the INFORMD2 context, the biogeochemical model provided critical output data for parameterizing one of the DSTs (Section 3.4). However, the DST does not replace the biogeochemical model, which continues to be the preferred platform for predicting long-term system-wide changes in water quality in response to changed nutrient loads or environmental conditions.

The CSIRO Environmental Modelling Suite (EMS) comprises a fully coupled hydrodynamic, sediment and biogeochemical model (http://www.emg.cmar.csiro.au/www/en/emg/software/EMS.html). It was implemented on the Derwent-Huon-D'Entrecasteaux (DHD) curvilinear grid and represented a continuation of an evolution of the model through a series of case studies in the area including the Aquafin CRC study of the D'Entrecasteaux Channel (Wild-Allen et al., 2010), the Huon Estuary Study (CSIRO Huon Estuary Study Team 2000) and the Derwent Estuary Modelling Study (Skerratt et al., 2013, Wild-Allen et al., 2013). The DHD model is similar in design to both the Derwent and D'Entrecasteaux models (Wild-Allen et al., 2010, Wild-Allen et al., 2013). However, the grid fully connects these two large estuarine systems (Figure 3.3) and is nested within the larger hydrodynamic model grid that was used for the connectivity modelling (Section 3.3).

The biogeochemical model cycled carbon, nitrogen, phosphorous and dissolved oxygen through dissolved and particulate organic and inorganic forms. It included multiple phytoplankton (small, large, dinoflagellate, microphytobenthos), zooplankton (small, large), macrophyte (seagrass, macroalgae), detritus (pelagic, benthic, refractory) and dissolved nutrient (inorganic, organic) components (Figure 3.4). Each biogeochemical component was represented by a tracer that was advected and diffused within the hydrodynamic model (in a similar manner to physical tracers such as temperature and salinity). Ecological particulate tracers could sink and be resuspended by the same formulation as sediment particles. At each ecological time step, non-conservative ecological rate processes such as growth, nutrient uptake, grazing and mortality were integrated within the ecological module, which returned updated tracer concentrations to the hydrodynamic and sediment models.

Loads of carbon, nitrogen and phosphorus entered the model domain across the offshore boundary, as well as rivers and a number of point source discharge locations throughout the region. Fluxes from offshore and river sources (Derwent, Huon, Jordon, and Esperance Rivers, and Northwest Bay Rivulet) are modelled as boundary conditions to the model. Loads from industry, sewage treatment plants and fish farms were included as point source loads delivered at specified locations and depths into the model domain (Figure 3.3).

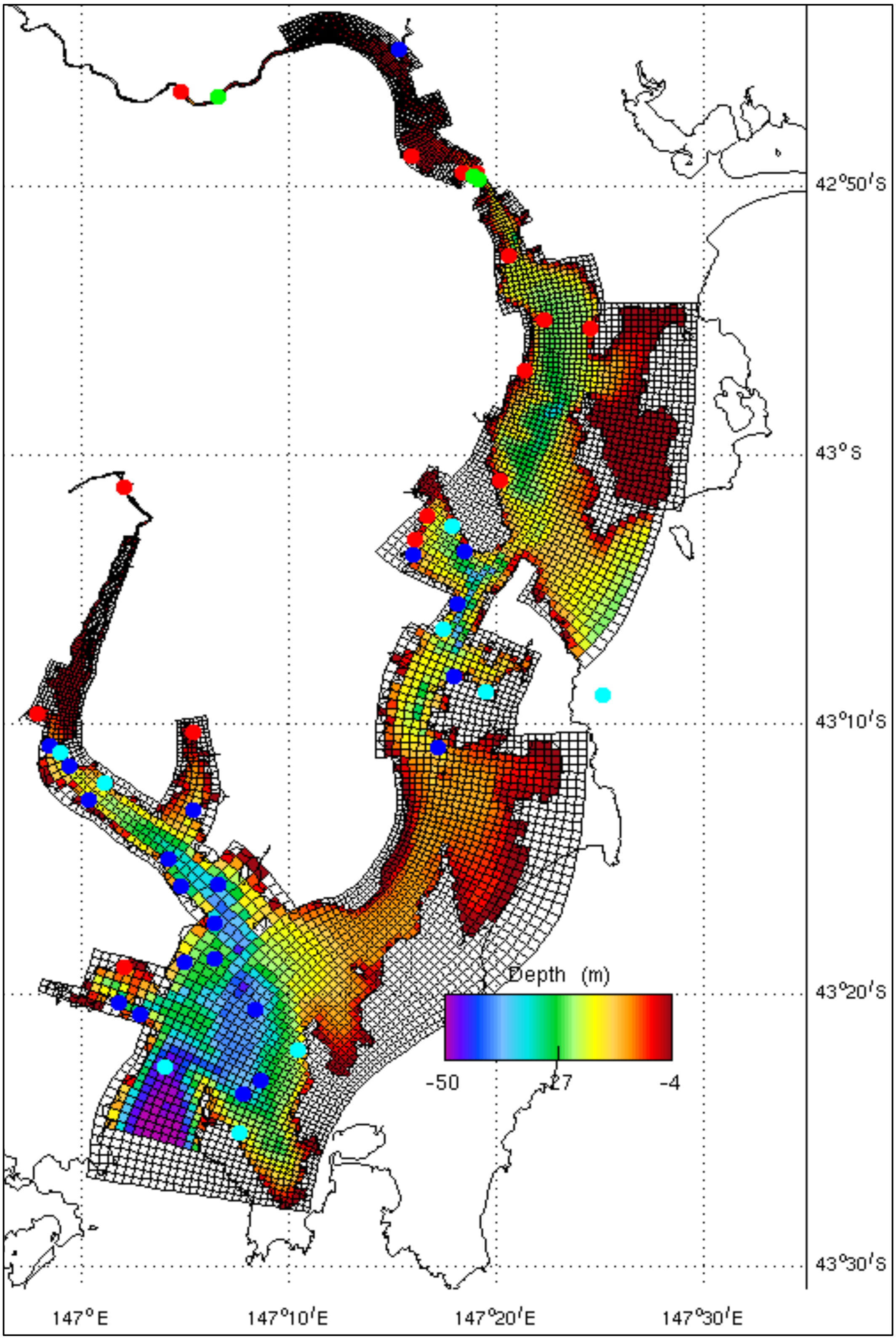


Figure 3.3: The DHD model grid and bathymetry with point source discharge locations shown for major rivers and point source loads from industry and sewerage sources (circles coloured to ensure visibility). There were four open boundaries: Huon and Derwent Rivers; southern D'Entrecasteaux boundary; and Storm Bay boundary. Horizontal grid spacing varied from <100 m in the upper estuaries to ~1 km in the Channel and the region outside the Derwent Estuary. There were 25 vertical layers associated with the grid ranging from 0.5 m thick at the surface to 10 m thick below 30 m depth (i.e. -60.0 -50.0 -40.0 -30.0 -25.0 -21.0 -17.0 -14.0 -12.0 -10.2 -9.0 -8.0 -7.1 -6.3 -5.6 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 m).

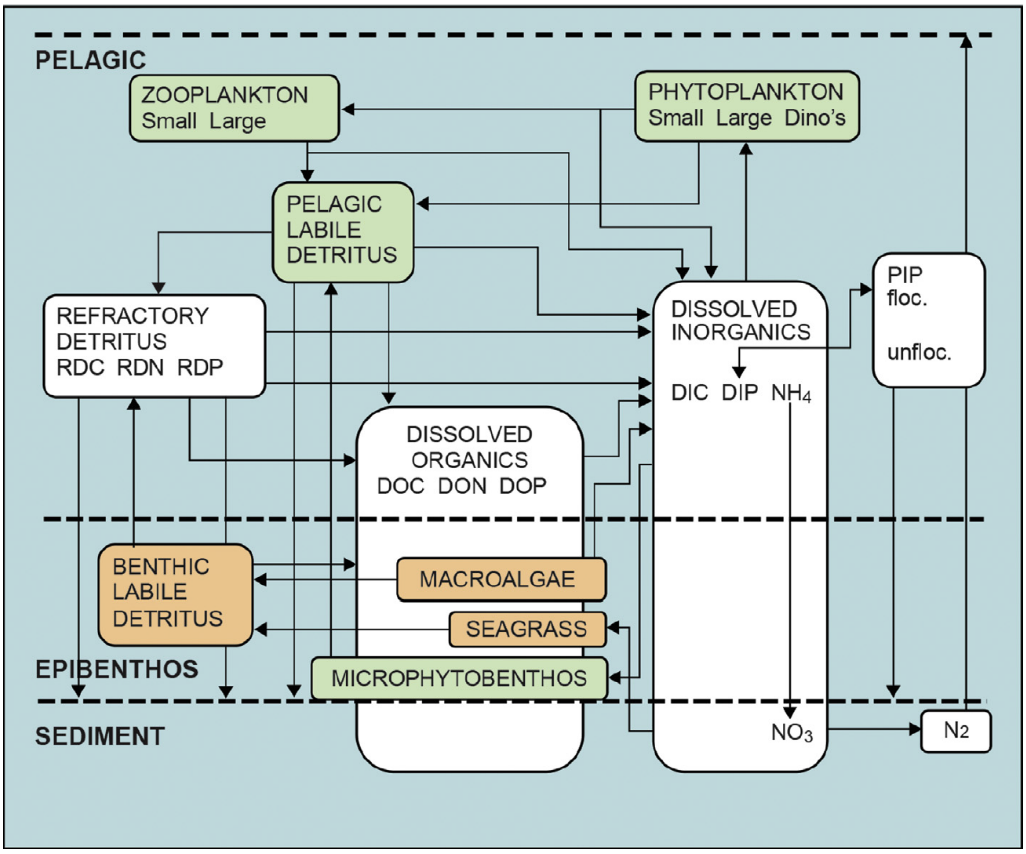


Figure 3.4: Components of the biogeochemical model (Wild-Allen *et al.*, 2013).

Model calibration

Biogeochemical process model parameters were largely based on previously reported simulations (Wild-Allen et al., 2010, 2013) that in turn were sourced from observations, previous modelling studies and literature studies relevant to the estuarine system. During model calibration poorly constrained biogeochemical model parameter values (such as phytoplankton mean cell size, growth rate and proportion of each functional group) were varied within known ranges to determine an optimal parameter set that produced model results consistent with observations.

The calibration was based on loads, boundary conditions and observations from January to December 2009. Comparisons with observations were undertaken at the 15 Broadscale Environmental Modelling Program (BEMP) sites and 13 Derwent Estuary Program (DEP) sites listed in Table 3.3.

Model performance was assessed in terms of the Willmott skill score *WSS* (Willmott, 1982):

$$WSS = 1 - \frac{\sum_N |mod(t) - obs(t)|^2}{\sum_N (|mod(t) - \overline{obs}| + |obs(t) - \overline{obs}|)^2} ; \quad (3.1)$$

where the model was sampled at N equivalent times t, locations and depths. WSS = 1 indicates that model and observations agree perfectly, whilst WSS = 0 indicates no agreement. A significant advantage of the Willmott skill score over more traditional correlation is that small errors in phase are not excessively penalised. The model bias was also estimated using:

$$Bias = \frac{1}{N} \sum_N (obs(t) - mod(t)) ; \quad (3.2)$$

A bias close to 0 indicates good agreement between model and observations on average.

Table 3.3: Locations of all *Virtual Monitoring Sites* (VMSs) selected in consultation with government and industry. The biogeochemical model outputs were compared with observations from the industry funded Broadscale Environmental Monitoring Program (BEMP) sites and the Derwent Estuary Program (DEP) sites. MAREE generates outputs at these same 28 sites, as well as 8 new sites (C1-C8).

Type	Site Name	Longitude	Latitude
BEMP sites	M1	147.340	-43.064
	M2	147.289	-43.055
	M3	147.292	-43.125
	M4	147.326	-43.135
	M5	147.297	-43.212
	M6	147.188	-43.316
	M7	147.208	-43.353
	M8	147.157	-43.432
	M9	147.068	-43.404
	M10	147.083	-43.256
	M11	147.090	-43.197
	M12	147.033	-43.330
	M13	146.982	-43.153
	M14	147.006	-43.204
	M15	147.126	-43.347
DEP sites	B1	147.340	-43.020
	B3	147.377	-43.024
	B5	147.400	-43.020
	U7	147.287	-42.790
	RBS	147.432	-42.983
	RBN	147.447	-42.925
	U4	147.312	-42.826
	RB	147.406	-42.951
	E	147.384	-42.919
	C	147.370	-42.970
	GB	147.349	-42.893
	U2	147.336	-42.852
	U12	147.228	-42.744
Additional INFORMD2 sites	C1	147.402	-43.050
	C2	147.388	-43.058
	C3	147.374	-43.066
	C4	147.254	-43.168
	C5	147.370	-43.198
	C6	147.322	-43.270
	C7	147.190	-43.288
	C8	147.042	-43.400

Model scenarios

The biogeochemical model was re-run using the 2009 forcing conditions combined with four alternative scenarios for point source nutrient loads (Figure 3.5). Government and industry representatives were consulted to identify the most relevant and useful scenarios, which can broadly be described as:

i. Near-pristine conditions – zero loads from sewage treatment plants and aquaculture.

ii. Recent conditions – 2009 loads from sewage treatment plants and aquaculture.

iii. Projected future conditions (low) – loads set 15% below the nitrogen cap for both the D'Entrecasteaux Channel region and Huon and Port Esperance region and (within these limits) redistributed toward the southern end of the D'Entrecasteaux Channel.

iv. Projected future conditions (high) – loads set at the nitrogen cap for both the D'Entrecasteaux Channel region and Huon and Port Esperance region and (within these limits) redistributed toward the southern end of the D'Entrecasteaux Channel.

The biogeochemical model can be used to test other load scenarios relating to changes in management practices or regulations. Examples include changes in stocking of existing lease areas (the focus of the three scenarios listed above), changes in zoning or allowable nutrient loads, and off-setting farm nutrient loads with changes to other industrial discharges or land-uses. New model runs are computationally intensive and require specialist biogeochemical modellers (hence the need for the DSTs described below). However, the biogeochemical model remains the only tool that can predict long-term system-wide changes in water quality.

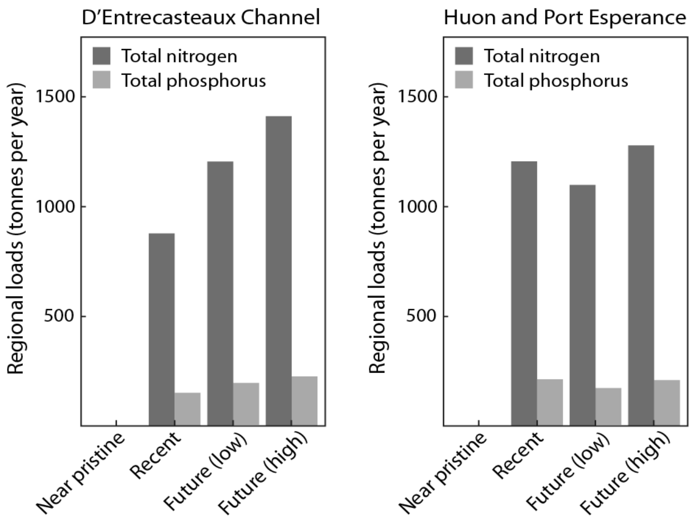


Figure 3.5: Regional loads for D'Entrecasteaux Channel and Huon and Port Esperance under the four scenarios. Loads have been aggregated at this regional scale to ensure confidentiality of projections at the scale of individual leases.

3.3 Dispersal and connectivity model: CONNIE3

Decision support tools representing marine dispersal have recently been developed to help site pens and determine stocking capacity for Southern Bluefin Tuna (*Thunnus maccoyii*) and Yellowtail Kingfish (*Seriola lalandi*) in South Australia's Spencer Gulf (CarCap 1.0; Middleton et al., 2013). This tool focuses on the flushing rate associated with ocean exchanges on the scale of individual leases and uses this information to estimate maximum feeding rates (Middleton et al., 2014). However, because the Tasmanian estuarine systems are much smaller in scale and more enclosed than Spencer Gulf, we need to consider not only flushing, but also upstream and downstream interactions of aquaculture and other marine activities and assets at relatively high spatial resolution.

Our dispersal and connectivity model used currents generated by a hydrodynamic model of the southeast Tasmanian estuarine and marine waters that included the Huon and Derwent Estuaries, D'Entrecasteaux Channel and Storm Bay (Figure 3.6). It was an extension of an earlier calibrated model covering part of the domain (Herzfeld et al., 2010) and solved the three-dimensional primitive equations on a finite-difference grid. The model was forced by winds, atmospheric pressure gradients, and surface heat and water fluxes from the Bureau of Meteorology operational meteorological model product ACCESS (http://www.bom.gov.au/australia/charts/about/about_access.shtml). It was also forced with river flow data (http://dpipwe.tas.gov.au/water/water-data/water-information-system-of-tasmania) and offshore boundary conditions such as tides and lower frequency sea-level variations from larger-scale models (http://www.emg.cmar.csiro.au/www/en/emg/projects/S-E--Tasmania/Project-description.html). Outputs from the model included sea-level and three-dimensional distributions of velocity, temperature and salinity (Figure 3.6).

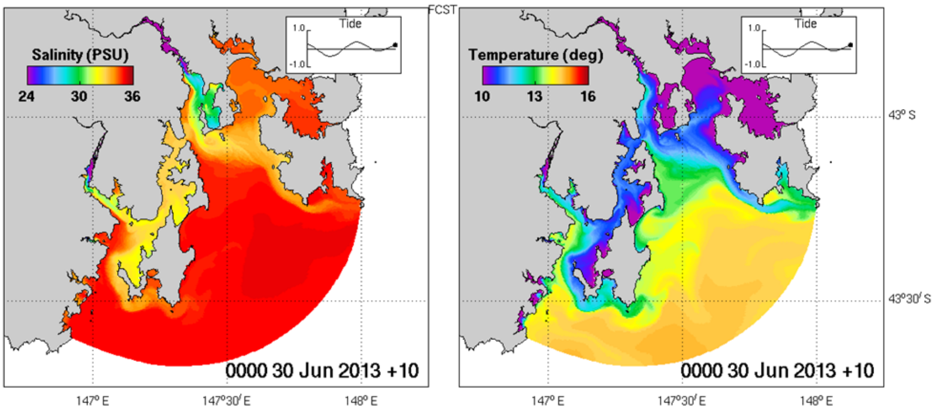


Figure 3.6: Examples of salinity (left) and temperature (right) outputs from the hydrodynamic model.

The online DST developed to model and visualise dispersal and spatial connectivity is referred to as CONNIE (CONNectivity InterfacE; www.csiro.au/connie/) and is the third generation of the tool having evolved over more than a decade (Condie et al., 2005). It combines currents from the hydrodynamic model with particle tracking techniques to estimate the zone of influence around pens or leases, as well as the influence of other activities on pens or leases. It includes an online graphical user-interface that allows government and industry to easily define and run scenarios.

The southern Tasmanian implementation of CONNIE has a spatial resolution of approximately 200 m, which is only a factor of 2 to 3 times greater than the size of individual salmon pens. It is automatically updated in near-real-time (monthly) to create an expanding archive. The graphical user-interface includes key data layers of interest to government and industry, such as aquaculture leases and monitoring sites, with the potential to include habitat layers in the future.

For each model run particles are seeded within the user-specified source (or sink) region at a constant rate of 100 particles per grid cell per day over the user-specified release period. This seeding rate adequately captures dispersal statistics, while maintaining relatively rapid computational rates. Following seeding, particles are tracked individually using a 4th-order Runge-Kutta ordinary differential equation (ODE) solver that linearly interpolates in time and horizontal space to find the horizontal velocity at the required depth and time. If the user specifies the direction as a source, then particles are tracked forward in time from the release. If the user specifies the direction as a sink, then particles are tracked backward in time ending at the release cells.

An additional horizontal velocity component (constant or random) can be added to represent unresolved current fluctuations or biological behaviour. Vertical migration can also be represented as instantaneous jumps between vertical levels. If a particle moves into an area where the deeper vertical level is beneath the seafloor, it will remain stationary until returning to the shallower level.

Graphical user interface

Particle distributions are represented on a geographical grid according to the following two options. The *final distribution* of particles within cells at the end of the user-specified dispersal time is expressed as a percentage of all the particles released (results sum to 100% over all cells). The *cumulative exposure* of cells to particles over the user-specified dispersal time is also expressed as a percentage of all the particles released (results sum to > 100% over all cells). If the user specifies a sink run, then these two options respectively show the initial upstream distribution and cumulative upstream exposure.

CONNIE utilises a map with familiar zoom and click-and-drag functionalities (Figure 3.7). On this map sources or sinks can be selected by clicking inside cells on a geographical grid. They can be deselected individually by clicking on cells a second time, or deselected all at once using the clear map button. Static data layers corresponding to reef habitats, bioregions, and various management zones can also be shown by clicking on ⊕ (top right of the map) and opening the map legend (Figure 3.7). After the user has specified other dispersal parameters (as described below) calculations are initiated using the submit button.

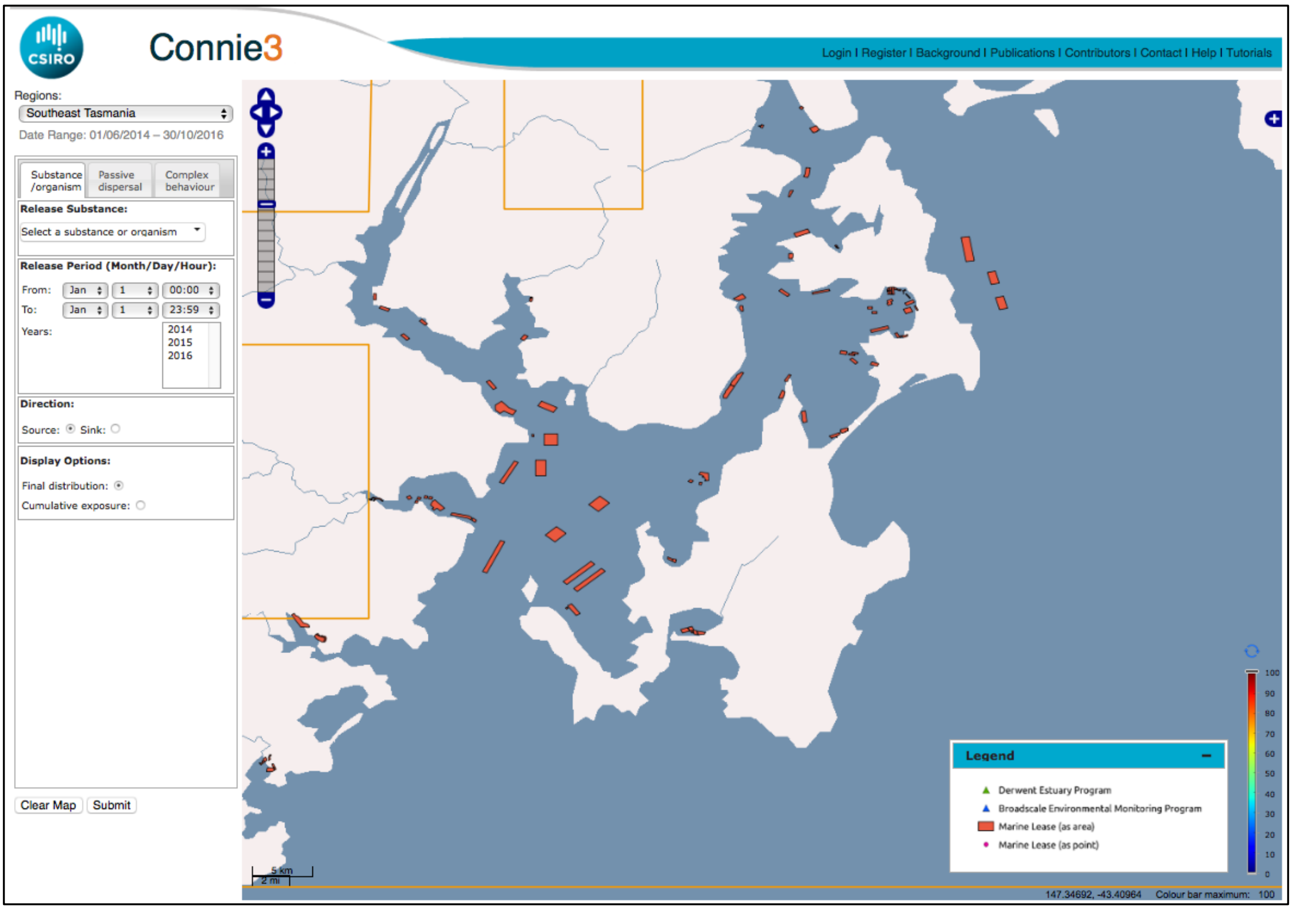


Figure 3.7: The online interface for CONNIE accessible at www.csiro.au/connie/.

CONNIE allows the user to select from three operating modes using tabs on the top right of the user-interface (Figure 3.8). Listed in order of increasing demands on the user to specify model parameters these modes are:

a. Select from a list of substances and organisms for which behaviours have been predefined on the basis of information from the scientific literature.

b. Assume passive dispersal at a single depth with the user specifying only the depth and the dispersal time.

c. Specify more complex combinations of physical and biological behaviours including vertical migration, horizontal propulsion, influence of wind, and chemical decay or biological mortality.

On completion of an online run users can save the results by clicking one of the three download options (lower left of the user-interface):

i. *Download last results image*, which can be saved as graphics file.

ii. *Download last results data*, which can be saved as a CSV file.

iii. *Download last results for Google Earth*, which can be saved as KML file.

If users are registered and logged-in, then outputs in all three formats are also available under *Saved Results*.

The ***Substance/organism*** mode of operation (Figure 3.8a) only requires the user to:

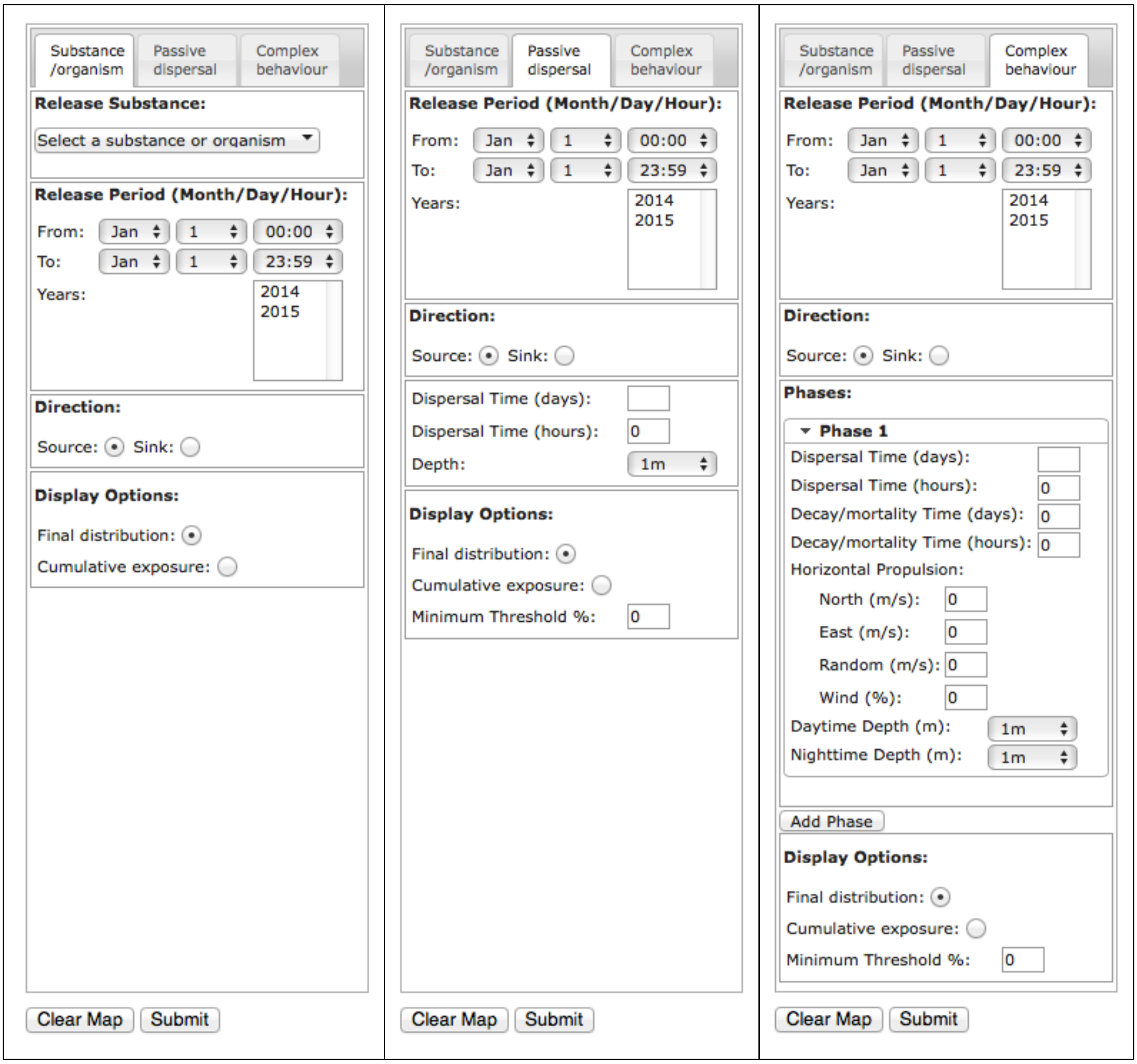
i. Select a substance or organism of interest from a list.

ii. Specify a particle release period (date and time). Multiple years can be selected to generate seasonal averages.

iii. Select an option for dispersal either downstream from a source or upstream to a sink.

iv. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

The list of substances and organisms currently available was chosen on the basis of stakeholder interests and availability of relevant data. It can be further expanded as required. Parameter values and associated references for each substance are provided in Appendix D, and for each organism in Appendix E. This documentation can also be viewed within CONNIE3 by selecting adjacent to the name of the substance or organism.



(a) (b) (c)

Figure 3.8: Fields from the CONNIE interface corresponding to the three modes of operation (selected using the tabs at the top). (a) Select from a list of substances and organisms for which behaviours have been predefined. (b) Assume passive dispersal with the user specifying only the depth and dispersal time. (c) Specify more complex combinations of physical and biological behaviours.

The ***Passive dispersal*** mode of operation (Figure 3.8b) requires the user to:

i. Specify a particle release period (dates and times). Multiple years can be selected to generate seasonal averages.

ii. Select an option for dispersal either downstream from a source or upstream to a sink.

iii. Specify a dispersal time (days and/or hours).

iv. Select a fixed water depth at which the dispersal occurs.

v. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

vi. Specify a minimum threshold for percentages to be shown on the display. This feature is typically used when concentrations below some level are not of relevance or concern.

The ***Complex behaviour*** mode of operation (Figure 3.8c) requires the user to:

i. Specify a particle release period (date and time). Multiple years can be selected to generate seasonal averages.

ii. Select an option for dispersal either downstream from a source or upstream to a sink.

iii. Specify a dispersal time (days and/or hours).

iv. If applicable, specify an exponential decay time or a mortality time (days and/or hours). This parameter can be used to model chemical transformation or mortality of biological organisms.

v. If applicable, specify any horizontal propulsion velocity to be added to the ocean current velocities. This may be in the form of constant north and east components, an uncorrelated random walk, a percentage of wind, or some combination of the three. A constant velocity may represent sustained swimming or propulsion of a vessel. The uncorrelated random walk or Brownian motion (Willis 2011) assumes all directions have equal probability and speeds are selected randomly from a Gaussian distribution where the specified speed corresponds to one standard deviation. This can be used to model either small scale physical mixing processes unresolved by the hydrodynamic model, or biological behaviours such as active foraging in productive environments (Humphries et al., 2010). Windage can be used to model the direct influence of wind on floating objects or surface slicks and therefore is generally only used in combination with the shallowest available depth.

vi. Select a daytime depth and a night-time depth. This can be used to model diurnal vertical migration, typically applied to organisms that feed near the surface at night and move to deeper levels in the day to avoid visual predators.

vii. Select an option to display either the final distribution of particles or the cumulative exposure of cells to particles (on the geographical grid).

viii. Specify a minimum threshold for percentages to be shown on the display. This feature is typically used when concentrations below some level are not of relevance or concern.

If the modelled substance or organism undergoes physical or chemical changes, or develops through multiple life-stages, then an arbitrary number of phases can be defined by selecting Add phase before adding different specifications for iii–vi.

3.4 Marine Ecological Emulator (MAREE)

The water quality DST is referred to as MAREE (MARine Ecological Emulator). It combines physical dispersal from CONNIE with a simplified representation of biogeochemical transformations (Figure 3.9). MAREE is capable of generating outputs for all the sites listed in Table 3.3 and is calibrated against outputs from the full biogeochemical model to ensure it provides information that is consistent with state-of-the-art biogeochemical modelling (albeit in a different format). Following initial testing within Microsoft Excel spreadsheets, MAREE has been implemented as an online tool similar to CONNIE.

Flow states and climate regimes

The first step in developing MAREE was identifying distinct flow states influencing dispersal that could later be used to define alternative climate conditions. Modelled flow patterns from a 12-month period (1 March 2008 to 28 February 2009) had previously been classified into nine states (A to I in Table 3.4) using a self-organising map (SOM) analysis with each described qualitatively in terms wind conditions and river discharge (Williams et al., 2014). We further quantified this classification using a principal component analysis (PCA). Variables included in the PCA included: the nine states; wind speed and direction over the central Channel (near site M6 in Table 3.3); and Huon River discharge measured at Judbury Bridge. This analysis distinguished just two underlying states, referred to here as State 1 and State 2. Using the wind and river discharge relationships identified through the PCA analysis over the period 2009 to 2015, daily conditions were mapped to one or other of the two states.

Three climate states were defined in terms of the frequency of the two flow states. A simple approach was to equate recent climate conditions with the 2009 to 2015 average percentages; then increase the percentage of State 2 for future climate scenarios. The rationale for increasing the frequency of State 2 over State 1 was that downscaled climate projections from the IPCC Fourth Assessment Report show increases in rainfall and extreme events in coastal Tasmania (Grose et al., 2010) with increased run-off in the Derwent Valley (Bennett et al., 2010) consistent with an increase in State 2.

Estimating the influence of new point source nutrient loads

The second step in the development of MAREE was to estimate the influence of user-defined loads of nutrients for each of the States using CONNIE upstream dispersal envelopes centred on the virtual monitoring sites (Figure 3.9). Since both local synoptic weather systems and many of the key biogeochemical transformations (e.g. uptake of nutrients and growth of algal blooms) tend to operate on timescales of order of a week in this system, a decay time of 7-days and a dispersal times of 7-days were combined with 1-day releases to generate an 8-day analysis window. This 8-day window and its associated upstream envelope were allocated to a particular state if the majority of days within the window had wind and river discharge conditions corresponding to that state in the PCA analysis. The 8-day window was then shifted 1-day forward and the analysis repeated until the ensemble of upstream envelopes spanned all of 2009.

The biogeochemical (BGC) model runs provided background loads at every virtual monitoring site (VMS) for each 8-day window. To this was added the effect of user-defined loads weighted by the upstream envelope for the same 8-day window. Biogeochemical transformations (beyond the 7-day decay) were determined empirically by fitting MAREE outputs to runs of the BGC model that included examples of user-defined sources. A combination of the background conditions, upstream envelopes and simplified biogeochemical transformations could then be used to estimate the conditions at all virtual monitoring sites under the changed loads (Figure 3.10). Mathematical details of the analysis are provided in Box 3.1.

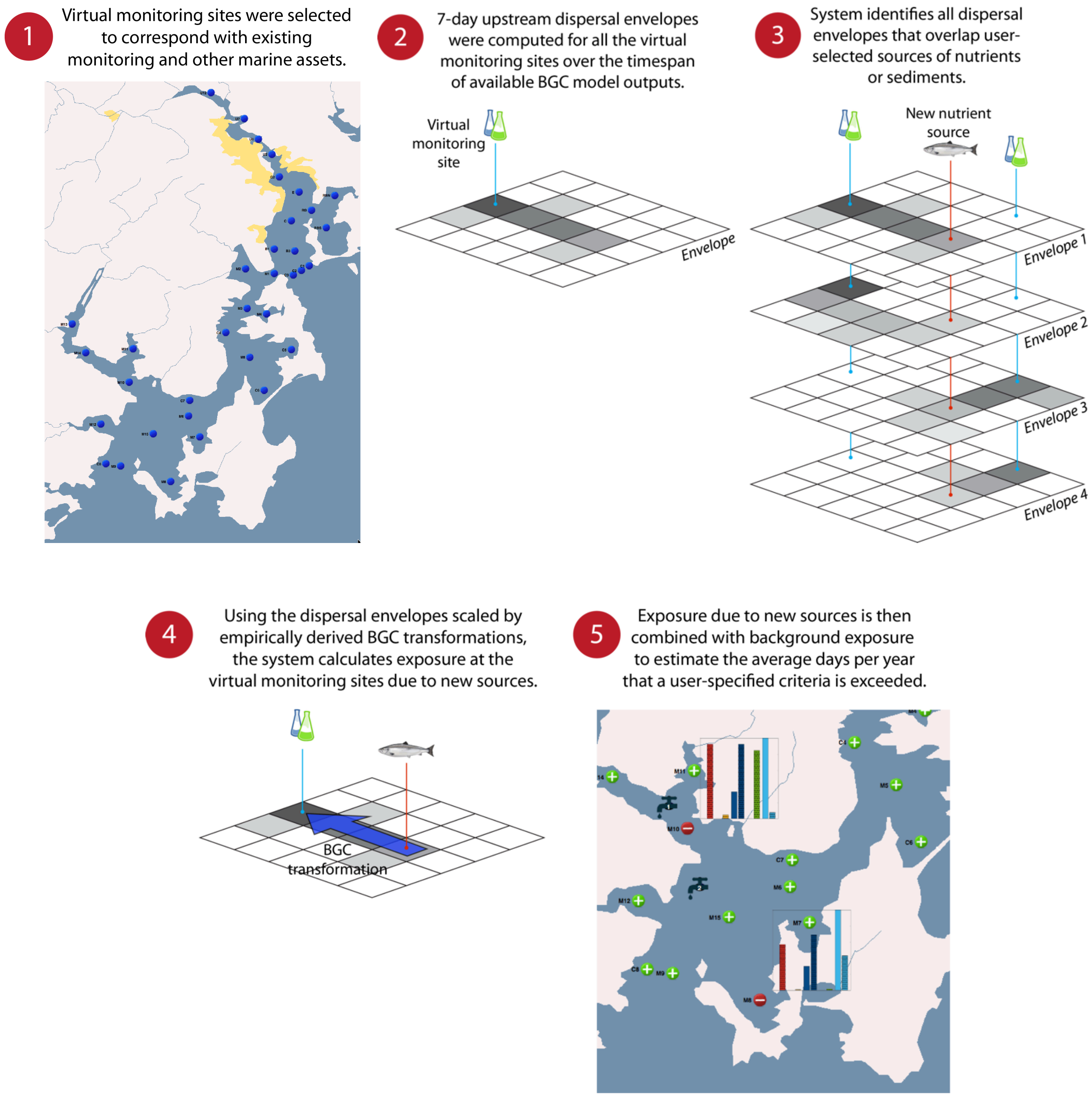


Figure 3.9: Summary of how MAREE works: (1) Outputs can be displayed at fixed virtual monitoring sites (VMSs). Most VMSs correspond to existing field monitoring or high value marine assets (Table 3.3). (2) Dispersal envelopes upstream of all VMSs have been computed using CONNIE and stored in a database. (3) Impacted VMSs can be identified using the overlap of dispersion envelopes with sites of new nutrient inputs selected by the user at run time (e.g. salmon pens). (4) Changes in conditions at the VMSs associated with the new nutrient loads are estimated from the dispersal envelopes scaled by empirical BGC transformations. (5) Results from the entire ensemble period are combined into a statistical description of the impacts of the new nutrient loads and visualised within the emulator.

Table 3.4: Classification of flow states based on a self-organising map (SOM) analysis (Williams *et al.*, 2014) and a principal component analysis (PCA).

	Prototype classification (based on a SOM analysis)	**Adopted classification (based on PCA)**
A	Weak to moderate river flow with strong northwesterly winds	State 1
B	Moderate river flow with moderate to strong northerly winds	
C	Moderate to strong river flow without wind influence	
D	Moderate river flow with variable winds	
E	Weak river flow with weak to moderate northerly winds	
F	Weak river flow with weak to moderate southerly winds	
G	Weak to moderate river flow with south-easterly winds	Mix of States 1 and 2
H	Strong river flow with weak winds	State 2
I	Weak to moderate river flow with strong southerly to south-westerly winds	

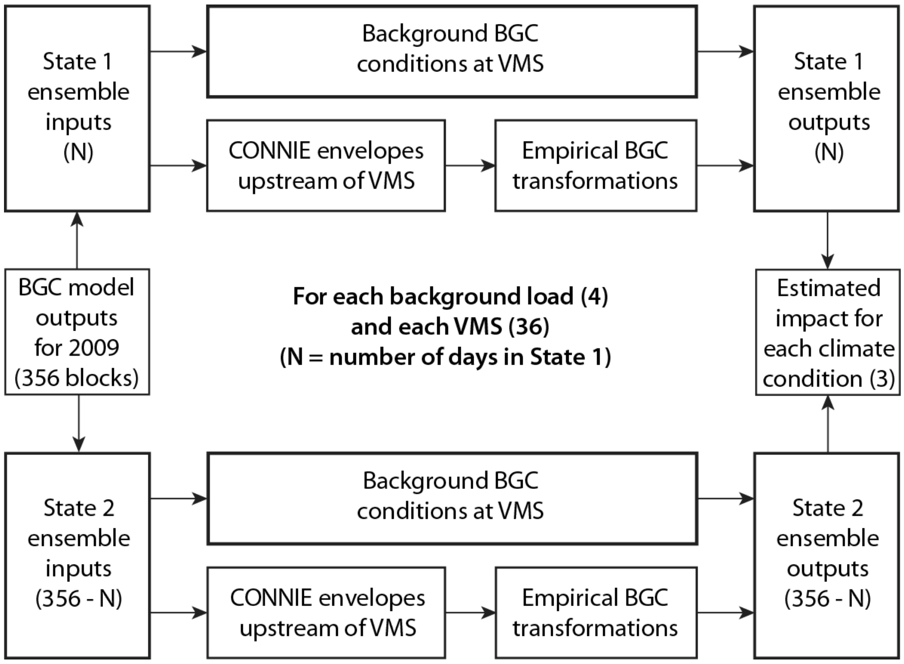


Figure 3.10: Flow of data associated with the MAREE calculations starting with outputs from the biogeochemical (BGC) model (365 – 7 = 358 8-day windows) split between States 1 and 2; and ending with a recombination of the states in proportions representative of the user-selected climate conditions.

Ensemble options

MAREE outputs are based on an ensemble of runs that are representative of the range of conditions that can occur in the estuarine system. This ensemble included:

i. The four options for background loads taken from the four nutrient loading scenarios run in the BGC model (Section 3.2).
ii. The three climate conditions defined in terms of relative frequency that flow States 1 and 2 occurred.

This approach allowed us to extrapolate results from the 2009 BGC model runs in a way that was statistically representative of historical conditions and likely future conditions.

Box 3.1: Mathematical formalism.

For a given State the concentration on day d at any virtual monitoring site (VMS) in MAREE is assumed to be the background concentration at the VMS plus contributions from any additional point source loads defined by the user:

$$C_M = C_B + K \sum_i L_i E_i \; ; \qquad (3.3)$$

where symbols are defined below. The effect of physical transport between point sources and VMSs is captured through the exposure term E_i, calculated for each day using CONNIE (averages based on a release period of 1-day, dispersal time of 7-days and a decay time of 7-days). The net effect of biogeochemical transformations is captured through the empirical constant K. The underlying assumption of using a constant value of K (for each background load regime and flow state) is that variability in concentrations beyond background levels is primarily controlled by transport from point sources to each VMS.

Following from equation (3.3) the calibration factor K was estimated as the median value of $(C_{BGC} - C_B)/\sum_i L_i E_i$ across all available days and all BGC calibration runs using a given set of background conditions. For the same background conditions, MAREE can then calculate the concentration C_M for any user specified load L_i from equation (3.3).

The exceedance at any VMS in MAREE (X_M) can be defined as percentage of days with $C_M > C_T$ (including both flow states). This can be compared with the background exceedance corresponding to the percentage of days with $C_B > C_T$ (X_B). We can also make an estimate of the uncertainty in X_M using equivalent exceedances calculated from the BGC model scenarios (X_{BGC}). Because we are comparing a long term cumulative statistic, each BGC scenario only provides a single point of comparison for each state and each exceedance level. A single error estimation formula was therefore derived from comparisons across all VMSs.

By plotting the difference in MAREE and BGC model exceedance estimates, $X_M - X_{BGC}$, as a function of the influence on exceedance of the additional loads, $X_M - X_B$, across a range of thresholds (1, 2, 3, 4, 5, 8, 10, 15, 20, 30, 40, 60, 80 and 100%), two point source load scenarios and all substances (ammonia, nitrate, DIN, DIP and chlorophyll) it was found that 98.3% of the BGC model results fell within the range:

$$X_M \in [X_B : 2X_M - X_B + 10] \; ; \qquad (3.4)$$

with an imposed upper cap of $\min(X_B + 25, 100)$. The minimum range is $X_M \in [X_B : X_B + 10]$ which occurs when $X_M = X_B$ (i.e. at VMSs where point source loads are estimated to have no direct influence on exceedance). Given that across all VMSs the error estimates correspond to either the 97th, 98th or 99th percentile (depending on the particular state and substance), they can be regarded as conservative from a management perspective.

With BGC responses satisfactorily captured by MAREE, the final step was to correct background load concentrations to account for any systematic bias in the BGC model as revealed through the calibration process (described below). Hence equation (3.3) was replaced with:

$$C_M = C_B - C_{bias} + K \sum_i L_i E_i \; ; \qquad (3.5)$$

Quantity	Definition
$C_B(d)$	Concentration calculated by BGC model with background loads for day *d* (mg/l)
$C_{BGC}(d)$	Concentration calculated by BGC model with additional loads (L_i) for day *d* (mg/l)
$C_M(d)$	Concentration calculated by MAREE with additional loads for day *d* (mg/l)
C_{bias}	Bias in BGC model concentrations relative to observations (mg/l)
C_T	Threshold concentration specified by user (mg/l)
L_i	Additional load at point source *i* specified by user (kg/d)
$E_i(d)$	Exposure of VMSs to point source location *i* on day *d* calculated using CONNIE (0 - 1)
K	Calibration factor (dependent on substance and State but assumed uniform across all VMSs)
X_B	Background exceedance equating to percentage of days with $C_B > C_T$
X_M	Exceedance with additional point source loads equating to percentage of days with $C_M > C_T$
X_{BGC}	Exceedance with additional point source loads equating to percentage of days with $C_{BGC} > C_T$

Graphical User Interface

The MAREE graphical user interface allows users to define new point sources of nutrients representing new coastal discharges or facilities such as sewage treatment plants or aquaculture pens (Figure 3.11). This requires the user to:

i. Select background loads that determine the background water quality conditions: *near pristine* corresponds to nil point source inputs (i.e. no sewage treatment plants or aquaculture inputs); *recent* corresponds to point source loads present in 2009; and *near future* (low or high) provides a range of future projected loads (including a redistribution towards the southern end of the Channel).

ii. Select the climate conditions corresponding to the recent past, near future or far future (see below).

iii. Select a depth option, where shallow equates to surface water (~1 m) strongly influenced by freshwater river discharge and wind, while midwater equates to a higher salinity water (~ 5m) more strongly influenced by marine inputs and bathymetry. Note that shallow sites do not have a midwater option (site icon remains blue).

iv. Select the location of the new point sources of nutrients by clicking on the map. The precise longitude and latitude of the cursor are shown at the bottom of the map.

v. Specify the loads of ammonia, nitrate, detrital nitrogen and dissolved inorganic phosphorus (DIP) associated with each source.

vi. Specify concentration thresholds for water quality measures (ammonia, nitrate, dissolved inorganic nitrogen (DIN), DIP and chlorophyll-a). The default values for these quantities correspond to the ANZECC guidelines (ANZECC 2000), but can be reset to align with user requirements.

vii. Select water quality measures to show in the results.

When the set-up is complete and the run submitted, results are viewed by clicking on any of the monitoring site icons on the map. Results from any monitoring site can be hidden again by clicking on. Results are in the form of bar graphs indicating the percentage of time that the user-specified thresholds are exceeded, first with only background loads and then with the additional sources included (Figures 3.11 and 3.12). These percentages combine measures of likelihood (exposure) and consequences (implicit in user-specified thresholds), and therefore can be interpreted as ecological risk probabilities.

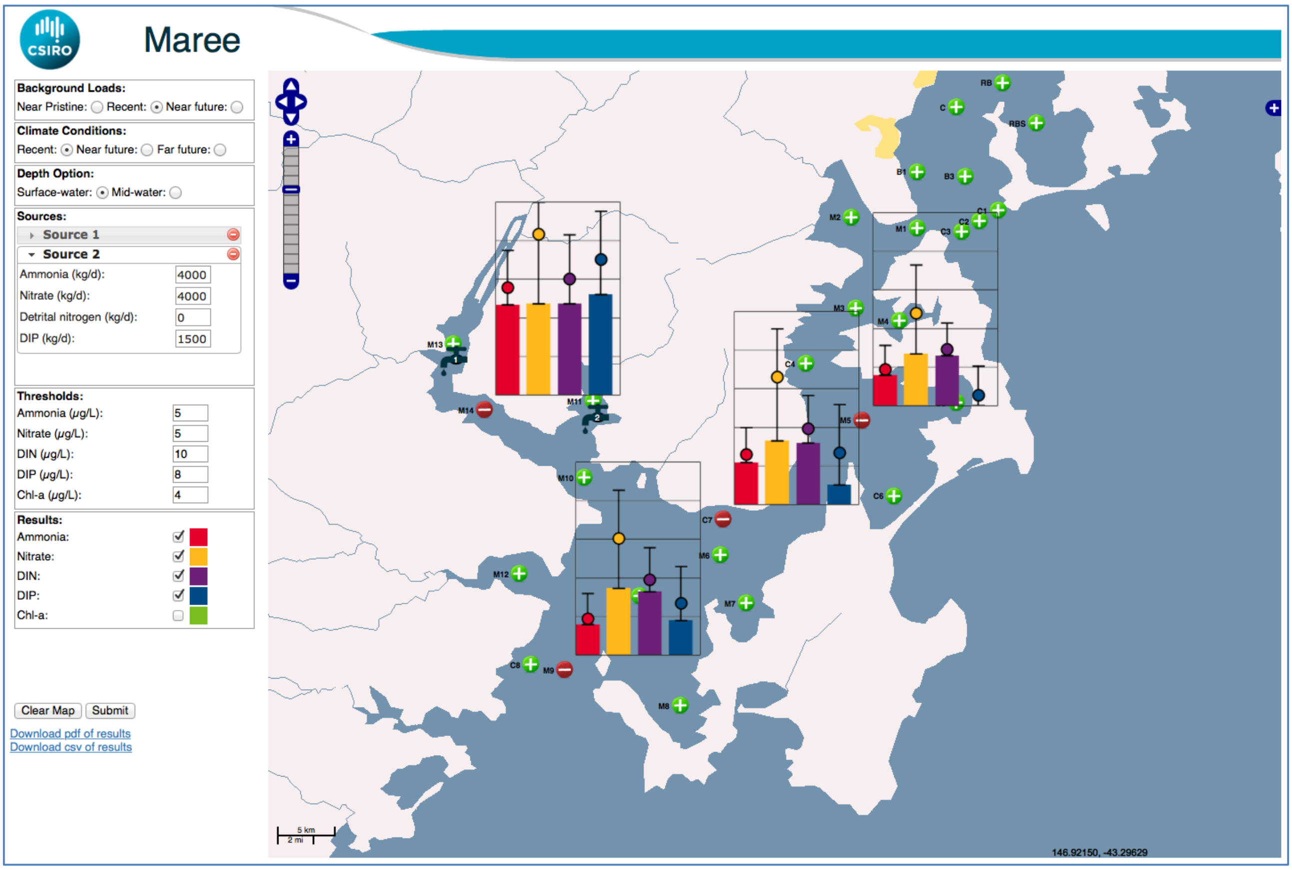


Figure 3.11: Graphical user-interface for the MAREE DST showing user-selected nutrient load sites (dripping-tap icons) and results at monitoring sites (bar graphs). Colour-coding of the bars is used to distinguish between water quality measures. The system can compare development or management scenarios and generate summary reports.

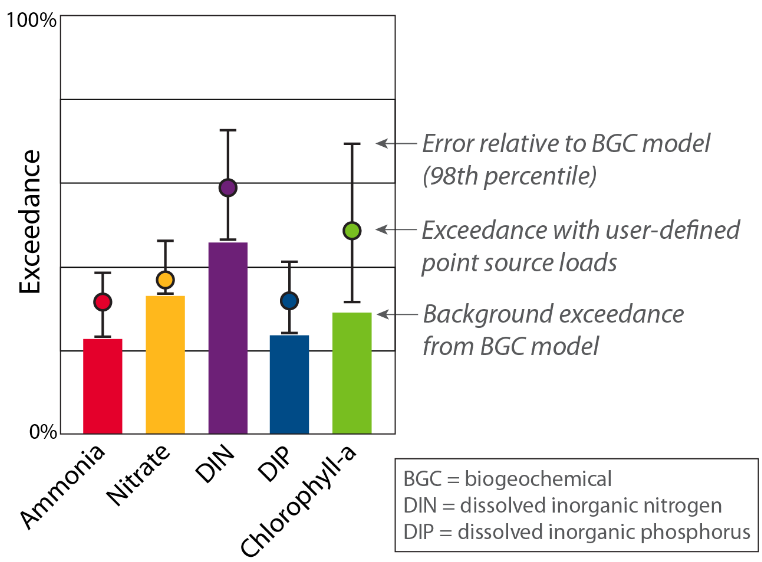


Figure 3.12: Elements of the bar graphs generated within the MAREE DST. Bars represent background exceedances and circles represent exceedances with additional user-defined point sources. The error bars represent the 97-99th percentile (average 98th) depending on the particular VMS.

4. Results

4.1 Your Marine Values

The YMV workshops identified 17 distinct values (Ogier and Macleod 2013). Interactions between these values were grouped in terms of the ecological processes and human activities that are significant at the estuary and channel scale. Values that were closely aligned and interacted with other values in similar ways were grouped so as to remove any redundancy in the matrix of network interactions (Table 4.1). The resulting 11 value groups could also be represented in the form of a digraph of network interactions describing the socio-ecological system (Figure 4.1). Both representations were used to refine and validate the network structure at the stakeholder workshops.

Loop analysis (Levins 1974) on the interaction network (Figure 4.1) revealed a number of network characteristics (Tables 4.2, 4.3 and 4.4):

i. Geological and geomorphological features (6) influence other values (column 6 of Table 4.3), but are not influenced by other values (row 6 of Table 4.3). Hence, they can be treated as an external driver of the network, rather than part of a feedback loop within the network.

ii. The remaining ecological values (2-3, 4 and 5) are more central to the network, being linked through a large number of complex feedback loops (Figure 4.1).

iii. The economic values of aquaculture and fishery industries (7 and 8) are also central to the network (Figure 4.1). However, the fishing industry has only a small footprint in the study region and only 5% of YMV participants included it in their value set (Ogier and Macleod 2013). While recreational fishing is more extensive, it was represented through ecological and social proxies.

iv. Marine tourism industry (9) and marine research and marine education (16-17) are influenced by many other values, but have no feedbacks into other parts of the network (columns 9 and 16-17 of Table 4.1). Hence, these values act as system indicators, rather than as part of a feedback loop.

v. Marine heritage (15) has feedbacks into marine tourism industry, but no other values (Figure 4.1, column 15 of Table 4.3). Similarly, the lifestyle related values (10-14) have feedbacks only into marine tourism and heritage (Figure 4.1, column 10-14 of Table 4.3). Being directly connected to many other values without being part of complex feedback loops, lifestyle related values provide useful system indicators in terms of both breadth and sensitivity.

These network characteristics provided guidance in the selecting elements to be represented in the DSTs:

i. Water quality (2) was the value identified by the largest number of YMV participants (68%) and is dynamically linked to almost every other identified value (Table 4.1, Figure 4.1). Hence it was central to the design of the DSTs.

ii. Marine habitats, communities and species (4 and 5) also have links to many other values (Figure 4.1) and hence key processes such as exposure to contaminants and larval recruitment dynamics were captured in the DSTs.

iii. While aquaculture industry (7) was clearly central to the study objectives, its inclusion in the DST also captured important system feedbacks (Figure 4.1).

iv. The lifestyle related values (9-13) are an important indicator group and the DSTs included elements such as water quality and dispersal of contaminants and debris that directly impact recreation amenity (10), seascapes (11), coastal landscapes (12) and marine environment (13).

Following these considerations, the final DST designs focused on the links highlighted by black lines in Figure 4.1. It is encouraging to note that the selected set of values were also the values identified by the largest number of stakeholders in the YMV workshops, with the remaining values identified by no more than 5% of respondents (Ogier and Macleod 2014).

Table 4.1: Influences of values (column headings) on other values (row headings) through ecological processes and human activities. Interactions likely to have a positive effect on a second value group are shaded in pale green, while those likely to a negative effect on a second value group are shaded in pale orange. For example, marine habitats are likely to have a positive effect on water quality through "removal of sediments, nutrients and contaminants by wetlands". Note that: (i) values were grouped where they were closely aligned and tended to interact with other values in similar ways; (ii) interactions were in the form of ecological processes or human activities associated with the values; (iii) only direct interactions have been included (i.e. not those operating via a third value); (iv) only interactions likely to be significant on the estuary/channel scale have been included (i.e. excluding highly localized or short-term interactions); and (v) an asterisk indicates processes that will be represented explicitly in the DSTs.

		Value exerting influence									
Value being Influenced	1. Tasmanian Aboriginal values	2. Water quality 3. Sediment quality	4. Marine habitats and communities	5. Marine species	6. Geological and geo-morpholog-ical features	7. Aquaculture industry	8. Fishing industry	9. Marine tourism industry	10. Recreation 11. Seascape 12. Coast 13. Marine environment 14. Lifestyle	15. Maritime heritage	16. Marine research 17. Marine education
1. Tasmanian Aboriginal values		Key contributing values	Key contributing values	Key contributing values	Often correspond to key heritage areas				Key contributing values		
2. Water quality 3. Sediment quality		*Nutrient balance to maintain ecosystem functioning	Removal of sediments, nutrients and contaminant by wetlands			*Inputs of nutrients, detritus and debris					
4. Marine habitats and communitie s		*Favourable light and nutrient conditions	Competition for substrate types and intertidal zone	Top-down control helps maintain diversity	Features provide substrate and other ecological niches						
5. Marine species		*Favourable light, oxygen and low toxicity conditions	Provide food and refuges from predators	Competition and predation			Extraction of fish				
6. Geological and geo-morphologic al features	Motivating protective legislation				Geological history						
7. Aquaculture industry		*Healthy stocks and high product quality		Damage to facilities and expense of exclusion		Regulation					
8. Fishing industry		High product quality		Higher catches and commercial returns			Regulation and available stocks				
9. Marine tourism industry		*Visual amenity and human health	Visual amenity	Key tourist attraction	Key tourist attractions and visual amenity	Key tourist attraction and local produce	Local produce	Competition for visitor trade	Key tourist attractions and visual amenity	Key tourist attractions	
10. Recreation 11. Seascape 12. Coast 13. Marine environment 14. Lifestyle	Motivating protective legislation	*Visual amenity, human and ecosystem health	Visual amenity and ecosystem health	Visual amenity and ecosystem health	Visual amenity	Access restrictions, noise and light pollution			*Population pressures on areas of high value		
15. Maritime heritage									All integral components of maritime heritage	Past history of preservation	
16. Marine research 17. Marine education	Traditional knowledge	*Focus increases as issues arise	Focus increases as issues arise	Focus increases as issues arise							Limitations in funding and student numbers

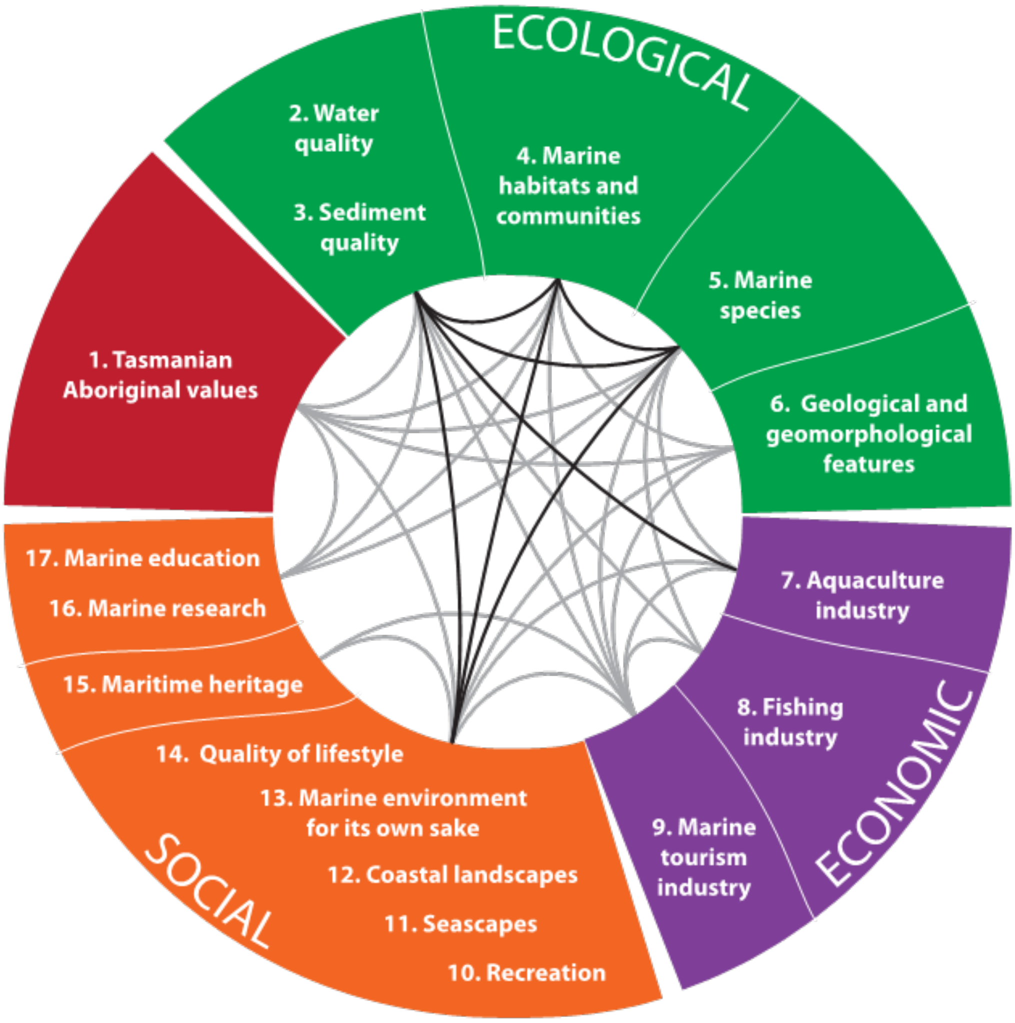


Figure 4.1: YMVs grouped and linked within a network of socio-ecological interactions represented in the form of a digraph. The subset of interactions captured in the DST is represented by black lines.

Table 4.2: Adjoint matrix for the network of all YMVs (except 1). The adjoint for the subset of YMVs that will be explicitly represented in the DSTs is shown in brackets. If the value shown in the column heading experiences a positive perturbation, then the sign of entries in that column indicate whether the net response (of the value listed in the row heading) is positive or negative (and vice versa for a negative perturbation).

	2-3	4	5	6	7	8	9	10-14	15	16-17
2-3	1 (0)	3 (1)	2 (1)	3	-1 (0)	-2	0	0 (0)	0	0
4	2 (2)	4 (2)	3 (2)	4	-2 (-2)	-3	0	0 (0)	0	0
5	1 (2)	2 (3)	1 (1)	2	-1 (-2)	-1	0	0 (0)	0	0
6	0	0	0	-1	0	0	0	0	0	0
7	0 (0)	1 (1)	1 (1)	1	-1 (-2)	-1	0	0 (0)	0	0
8	2	5	3	5	-2	-4	0	0	0	0
9	14	31	20	27	-13	-21	-1	-2	-1	0
10-14	4 (4)	8 (5)	5 (3)	7	-3 (-2)	-5	0	-1 (-2)	0	0
15	4	8	5	6	-3	-5	0	-1	-1	0
16-17	-4	-9	-6	-9	4	6	0	0	0	-1

Table 4.3: Number of feedbacks within the network of all YMVs (except 1). The number of feedbacks within the subset of YMVs that will be explicitly represented in the DSTs are shown in brackets.

	2-3	4	5	6	7	8	9	10-14	15	16-17
2-3	3 (2)	3 (1)	2 (1)	3	3 (2)	2	0	0 (0)	0	0
4	4 (2)	6 (2)	3 (2)	6	4 (2)	3	0	0 (0)	0	0
5	3 (2)	4 (3)	3 (3)	4	3 (2)	3	0	0 (0)	0	0
6	0	0	0	13	0	0	0	0	0	0
7	6 (2)	5 (1)	3 (1)	5	7 (4)	3	0	0 (0)	0	0
8	4	5	5	5	4	8	0	0	0	0
9	52	59	38	111	55	41	13	26	13	0
10-14	16 (8)	18 (7)	11 (7)	31	17 (10)	11	0	13 (6)	0	0
15	16	18	11	44	17	11	0	13	13	0
16-17	10	13	8	13	10	8	0	0	0	13

Table 4.4: Weighted predictions for the network of all YMVs (except 1). The weighted predictions for the subset of YMVs to be explicitly represented in the DSTs are shown in brackets. The weighted prediction is the net number of positive or negative feedbacks divided by the total number of feedback (Table 4.3). A weighted prediction of 1.0 indicates that the predicted qualitative response (Table 4.2, Figure 4.2) is certain (for that network structure); a value < 1.0 and ≥ 0.5 indicates that the prediction is likely; and a value < 0.5 indicates that the prediction is highly uncertain (Dambacher et al., 2003, Hosack et al., 2008).

	2-3	4	5	6	7	8	9	10-14	15	16-17
2-3	0.33 (0)	1 (1)	1 (1)	1	0.33 (0)	1	0	1 (1)	0	0
4	0.5 (1)	0.67 (1)	1 (1)	0.67	0.5 (1)	1	0	0 (1)	0	0
5	0.33 (1)	0.5 (1)	0.33 (0.33)	0.5	0.33 (1)	0.33	0	0 (1)	0	0
6	1	1	1	0.08	1	1	1	1	1	1
7	0 (0)	0.2 (1)	0.33 (1)	0.2	0.14 (0.5)	0.33	0	1 (1)	0	1
8	0.5	1	0.6	1	0.5	0.5	1	0	0	1
9	0.27	0.53	0.53	0.24	0.24	0.51	0.08	0.08	0.08	1
10-14	0.25 (0.5)	0.44 (0.71)	0.45 (0.43)	0.23	0.18 (0.2)	0.45	0	0.08 (0.33)	0	0
15	0.25	0.44	0.45	0.14	0.18	0.45	0	0.08	0.08	0
16-17	0.4	0.69	0.75	0.69	0.4	0.75	0	0	0	0.08

Implications of the selection of values for the dynamical responses of the system were tested by comparing the qualitative responses of the model including all YMVs with that of a model based on the reduced set of YMVs included in the DSTs (Figure 4.2). This comparison was based on the following three relevant scenarios: (a) a decline in water quality; (b) a decline in marine habitats and communities; and (c) an increase in the aquaculture industry. The qualitative response of the two models was the same in both cases except that in scenarios (a) and (c) water/sediment quality changed from decreasing to balanced. However, because there is a high level of uncertainty in both predictions, there is no contradiction between the models. The reduced model should therefore provide an appropriate representation for the purposes of the DSTs.

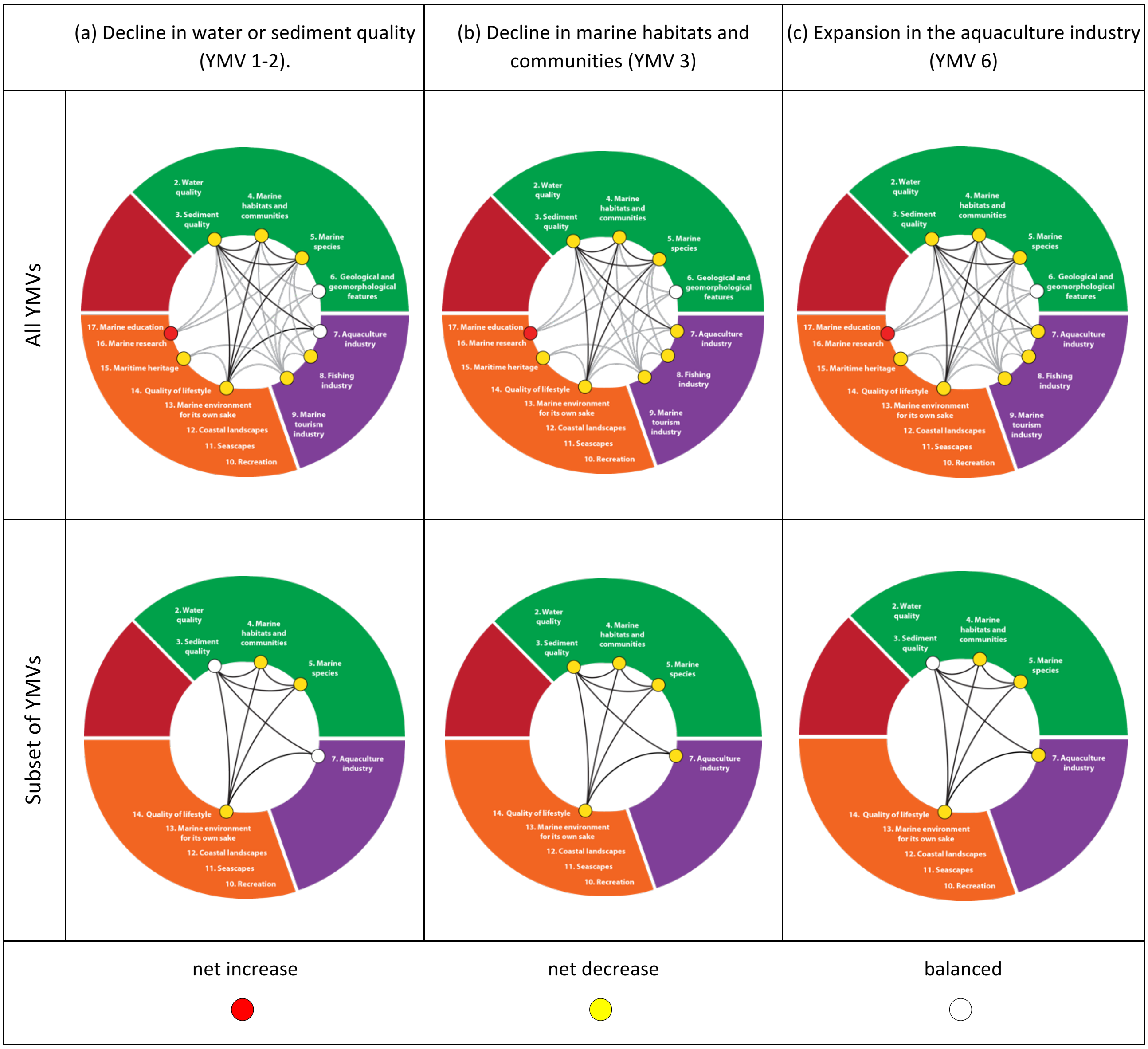


Figure 4.2: Qualitative responses of networks containing all of the YMVs apart from Tasmanian Aboriginal values (upper) and the subset of YMVs to be explicitly represented in the DSTs (lower). (a) Responses to a decline in water and/or sediment quality. The only difference in the two responses is in water/sediment quality itself (2-3), where the weighted predictions are highly uncertain. (b) Response to a decline in marine habitats and ecological communities, where the responses are identical. (c) Response to an expansion in the aquaculture industry. The only difference in the two responses is again in water/sediment quality (2-3), where the weighted predictions are again highly uncertain.

4.2 Biogeochemical model

The calibration of the biogeochemical model was based on loads, boundary conditions and observations from January to December 2009. Comparisons with observations have been undertaken at the 36 sites listed in Table 3.3.

Regional summaries of comparisons with the industry monitoring data (BEMP) demonstrated good agreement in DIN levels with realistic seasonal patterns in the Huon Estuary, D’Entrecasteaux Channel and Derwent Estuary (Figure 4.3a). The main discrepancies were a tendency to underestimate autumn DIN in the Huon and winter DIN in the D’Entrecasteaux resulting in overall negative biases. However, Willmott skill scores were relatively high given unavoidable mismatches in the scales of observations and modelling.

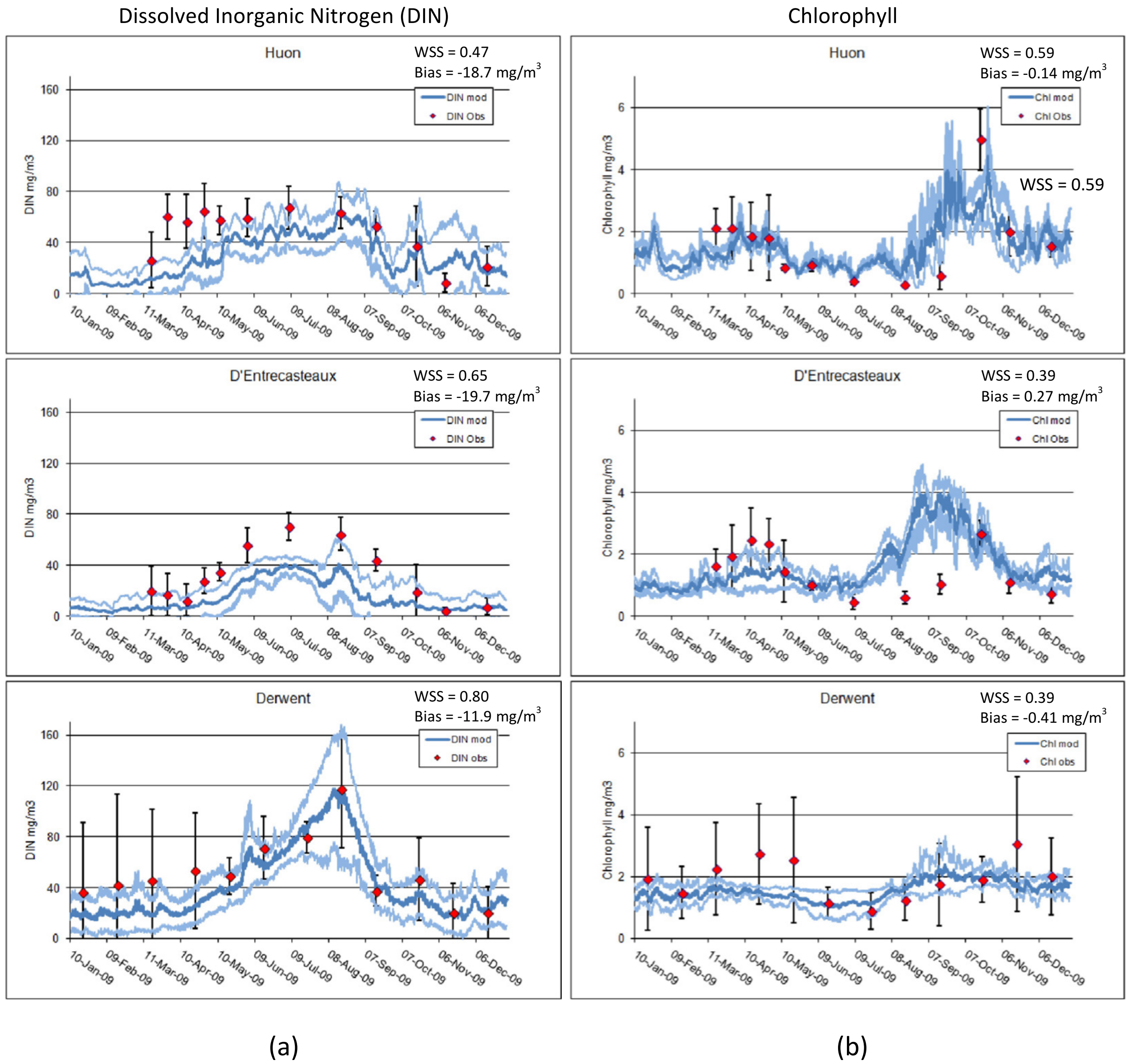


Figure 4.3: Comparison of observations (red points = regional mean, error bars = standard deviation) and model outputs in three regions (dark blue = regional mean, light blue = standard deviation) for (a) DIN; and (b) chlorophyll. In each case the Willmott skill score and model bias are shown in the top right. Adapted from Wild-Allen and Andrewartha (2016).

Modelled chlorophyll also showed generally good agreement with observations, reproducing the observed autumn and spring blooms (Figure 4.3b). The main discrepancy was premature onset of the spring bloom in the D'Entrecasteaux, which may have contributed to excessive uptake of nutrients and the aforementioned underestimate of winter DIN. This also resulted in an overall positive bias in D'Entrecasteaux, whereas the other two regions had a negative bias. Willmott skill scores were again satisfactory given mismatches in the scales of observations and modelling.

The model DIN results showed clear spatial signatures of the anthropogenic loads (Figure 4.4a) during summer (Figure 4.4b), but much less so in winter (Figure 4.4c) when river and offshore inputs were more significant (Figure 4.4d-f). There is a corresponding chlorophyll response downstream of point source loads during summer (Figure 4.4g) and within mixing zones where offshore waters combine with estuary water during winter (Figure 4h) and spring (Figure 4.4i-k).

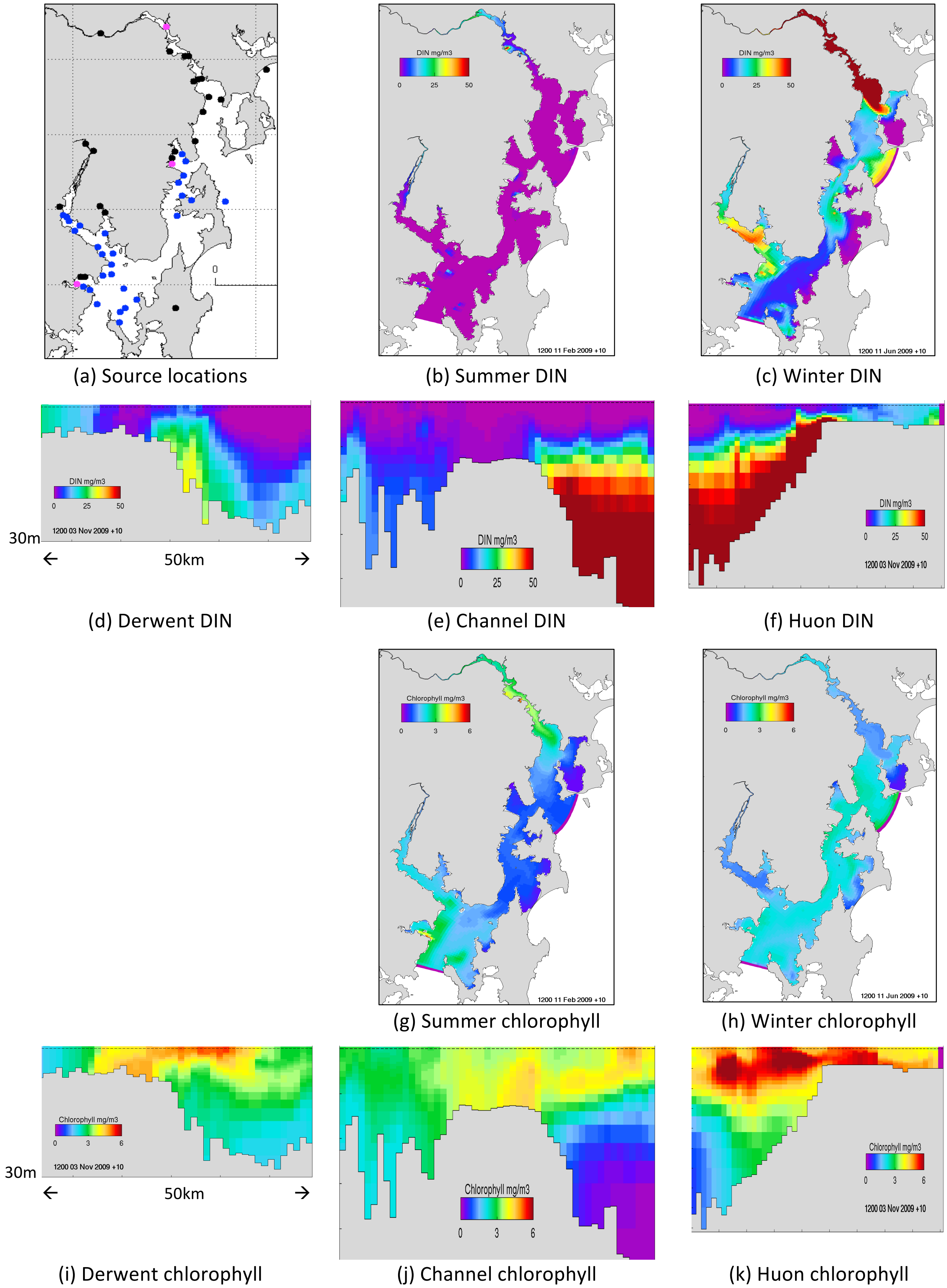


Figure 4.4: (a) Positions of sewerage treatment plants (black), fish farm leases (blue), and minor rivers (pink) included in the DHD model. DIN levels: (b) at the surface during summer; (c) at the surface during winter; and vertical sections during November in the (d) Derwent; (e) Channel; (f) Huon. Corresponding chlorophyll levels: (g) at the surface during summer; (h) at the surface during winter; and vertical sections during November in the (i) Derwent; (j) Channel; (k) Huon.

The main applications of the biogeochemical model to date have been running the various scenarios used to set background levels and calibrate MAREE (Section 3.4) and to estimate nutrients budgets. As an example of the latter, the seasonal nitrogen budget for the entire system suggests that in summer point source inputs (associated mainly with sewage discharges in the Derwent and fish farms in the Huon and Channel) are largely offset by denitrification and marine export into Storm Bay. Whereas in winter, river, marine and point source loads are all significant and offset by marine export and some denitrification (Figure 4.5).

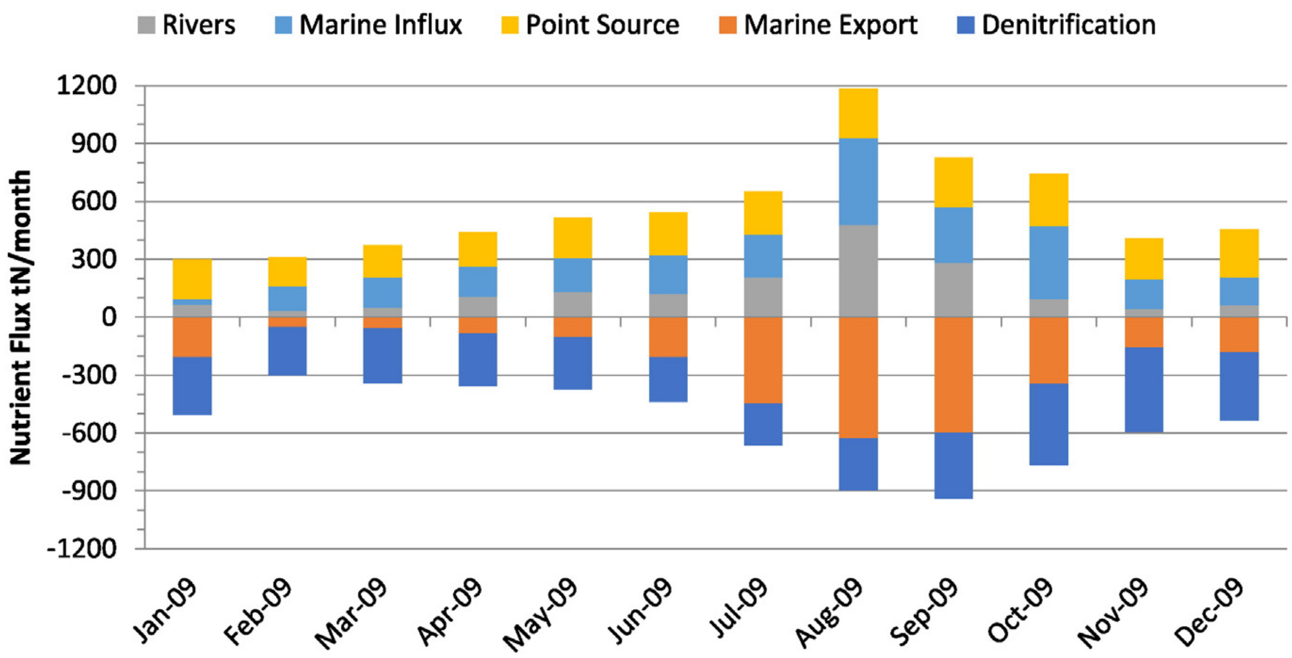


Figure 4.5: Nitrogen flux into (positive) and out of (negative) of the biogeochemical model region. Point source loads include fish farms, sewerage and industry discharges (Wild-Allen and Andrewartha 2016).

4.3 CONNIE3

The functionality provided by CONNIE3 can be illustrated through a series of examples addressing specific issues that have arisen during the study. However, we begin by demonstrating that predicted dispersal patterns match expectations in relation to the residual (sub-tidal) circulation in the D'Entrecasteaux Channel and Huon Estuary (Figure 4.6). Particles released near the surface in the Huon were carried into the Channel where they separate into two paths, one directed south along the Channel and one east and north (Figure 4.6b). This residual flow pattern is consistent with an earlier calibrated model (Figure 4.6a). Particles released near the bottom in the southern Channel were mainly carried northeast before separating into a southward path and a northward path into the Huon (Figure 4.6c). This is again consistent with the earlier findings (Figure 4.6a).

Over the course of the study there has been strong user uptake of CONNIE3, particularly within government and among salmon companies. This is perhaps best demonstrated by its adoption as a major element in the development of Environmental Impact Statements (EIS) for the proposed expansion of salmon aquaculture into Storm Bay. A standard parameterisation for representation of dissolved nutrients in CONNIE3 has been agreed between the regulators (DPIPWE and EPA) and the companies (Appendix F). This will allow all parties to generate consistent model runs that are directly comparable. As part of this arrangement, DPIPWE has commissioned CONNIE3 runs that combine the proposed nutrient loads from all lease sites and making the results available to each of the companies for inclusion in their individual EIS. Descriptions of three further CONNIE3 applications are provided below.

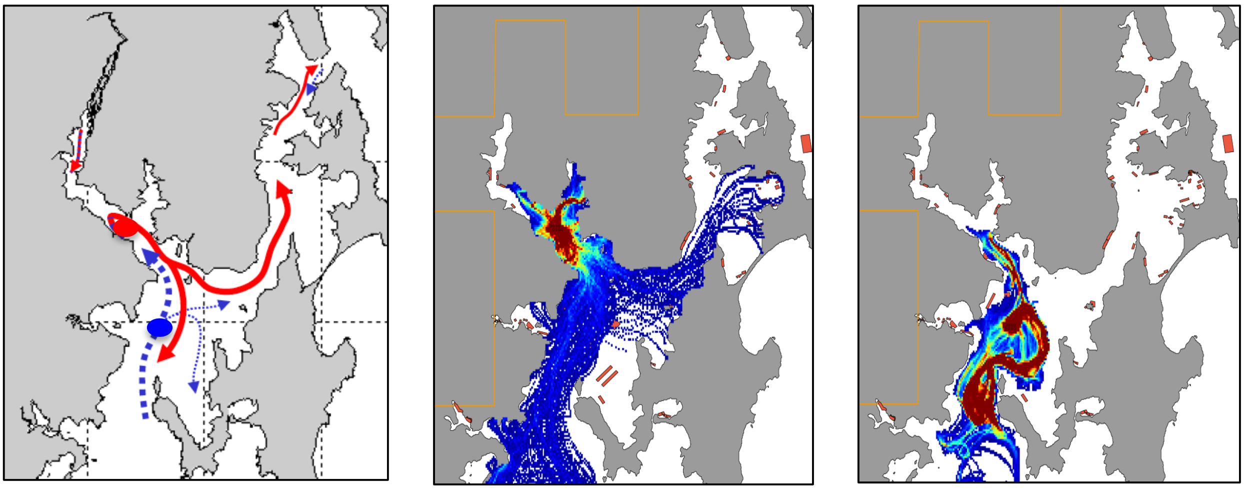


Figure 4.6: (a) Conceptual residual flow pattern near the surface (red) and bottom (blue) in the D'Entrecasteaux Channel and Huon Estuary (Herzfeld et al., 2010). (b) Dispersal from a surface release in the Huon in June 2014 at the site shown by the red ellipse in (a). (c) Dispersal from a bottom release in the Channel in June 2014 at the site shown by the blue ellipse in (a). Dark red in (b) and (c) indicates that more than 5% of particles passed through that cell, while dark blue indicates less than 0.5%.

Application 1: Potential for interaction between salmon aquaculture and abalone reefs

The capabilities of the dispersal model can be demonstrated through an analysis of the potential exposure of the main abalone populations in the lower D'Entrecasteaux Channel (Actaeon Reef) to upstream influences of salmon leases (focus of the 2015 Senate Inquiry: http://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/Fin-Fish/Report). For this purpose we focused on two leases in the southern channel. Results from summer and winter in 2015 show dispersal of a range of substances (Figures 4.7 and 4.8). Salmon faeces was transported by the tides before settling within 2 km of farm pens (Figure 4.7a,b), while biofouling dislodged during the cleaning of pens generally settled within 1 km (Figure 4.7c,d). Neither of these substances is likely to interact directly with the abalone reefs to the south.

Dissolved substances such as nutrients remain in the water column and are potentially dispersed over a large region that sometimes includes Actaeon Reef and southern Bruny Island (Figure 4.8a,b). However, dilution and uptake by phytoplankton ensures that concentrations fall to extremely low levels in the southern D'Entrecasteaux Channel (< 1% of that in the lease area) and are therefore likely to be indistinguishable from background levels (Figure 4.8c,d).

An alternative approach to the same issue is to use the dispersal model to identify the upstream sources of water flowing around Actaeon Reef. Using the worst-case scenario of a dissolved substance with no chemical breakdown or biological uptake, we can identify rare instances of connectivity between lease areas and Actaeon Reef (Figure 4.9). However, together the various analyses (Figures 4.7 to 4.9) suggest that direct impacts of salmon aquaculture on the reef are likely to be negligible.

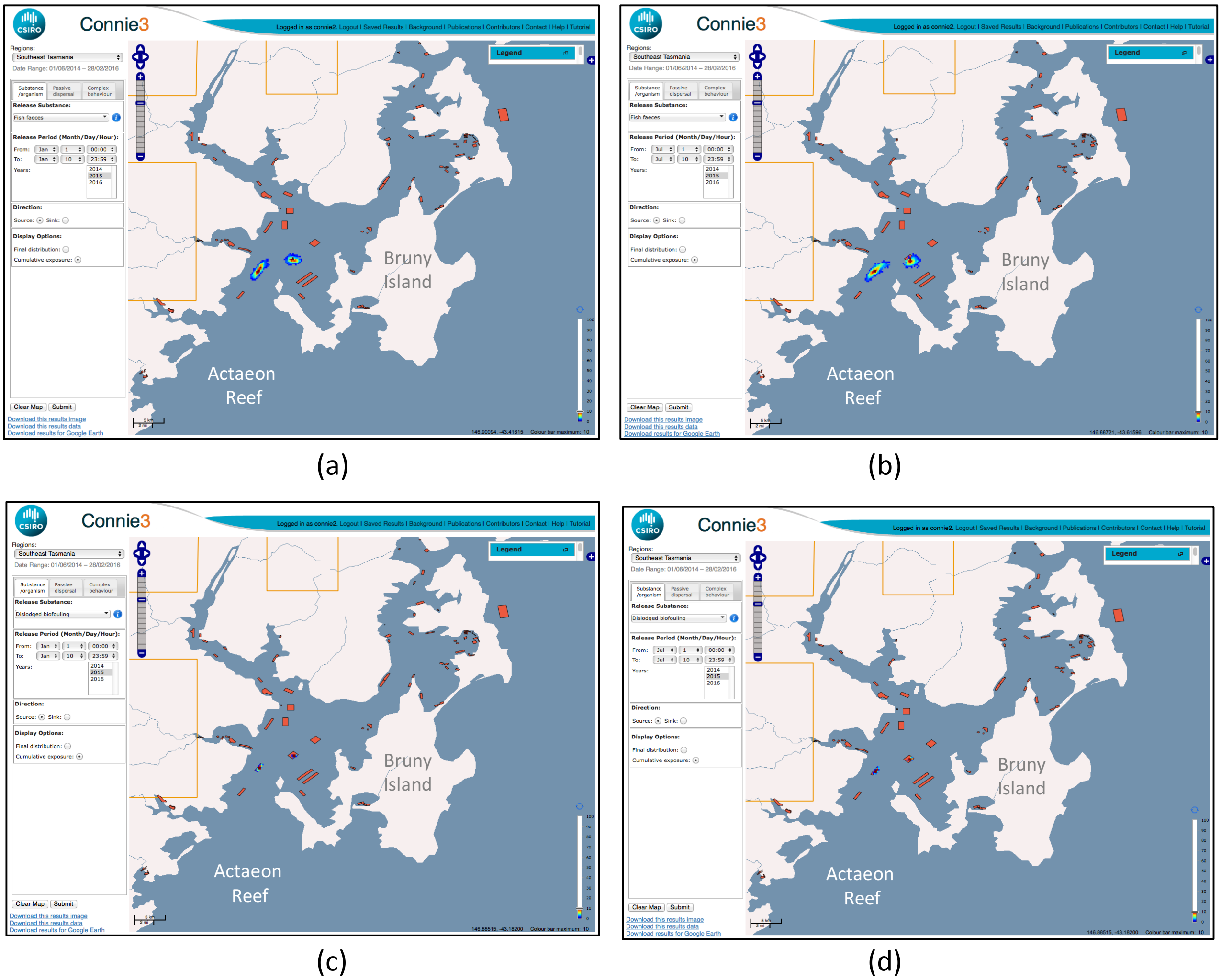


Figure 4.7: Modelled exposure to substances released from two salmon leases in the southern D'Entrecasteaux Channel during 2015. (a) Fish faeces released in early January and (b) early July. (c) Biofouling dislodged during the cleaning of pens in early January and (d) early July. Aquaculture leases are indicated by orange boxes (more recent are shown in Figure 3.7) and exposure ranges from < 2% (dark blue) to > 10% (dark red) of the release.

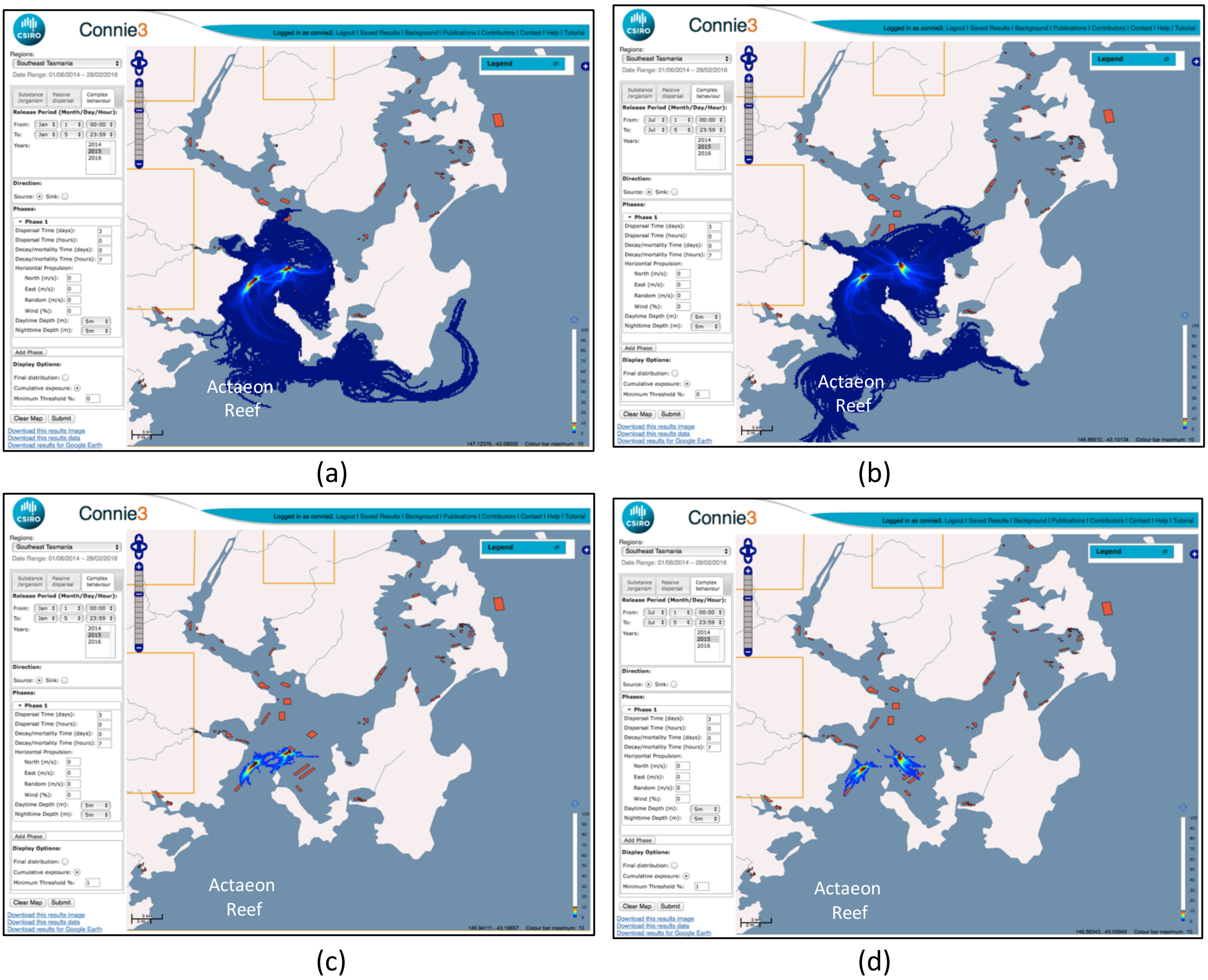


Figure 4.8: Modelled exposure of surrounding waters to dissolved substances released from two salmon leases in the southern D'Entrecasteaux Channel during 2015. (a) Nutrients with an uptake timescale of 7 days released in early January and (b) early July. (c) Same as (a) but with exposure levels < 1% of those within the lease area removed. (d) Same as (b) but with exposure levels < 1% of those within the lease area removed. (c) and (d) Aquaculture leases are indicated by orange boxes (more recent are shown in Figure 3.7) and exposure ranges from < 2% (dark blue) to > 10% (dark red) of the release. The additional nutrients indicated by the large area of dark blue in (a) and (b) would be indistinguishable from background levels.

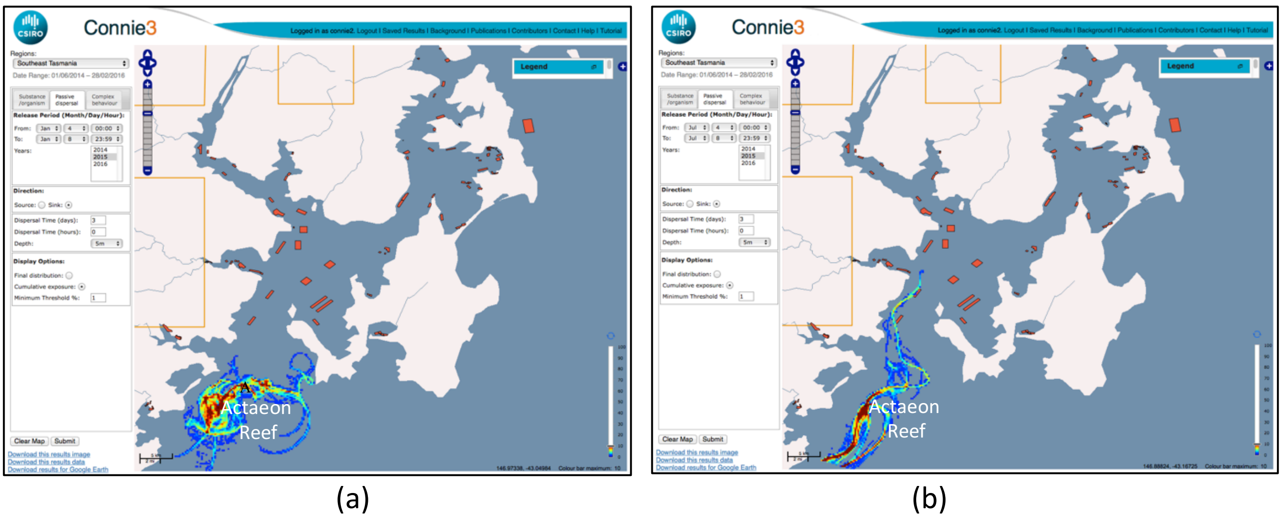
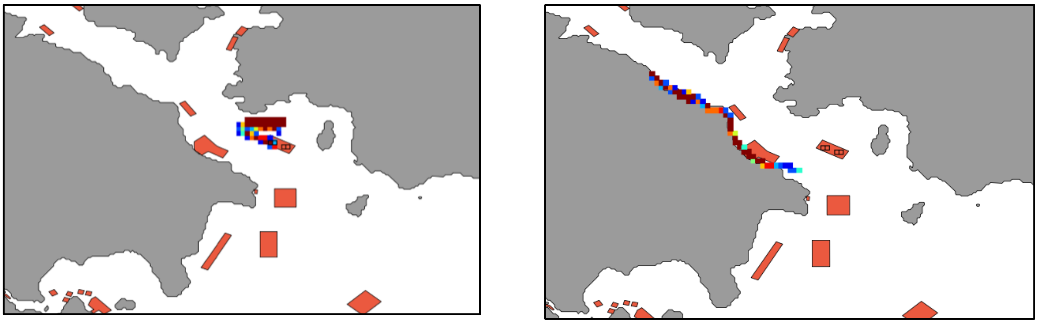


Figure 4.9: Modelled upstream sources of water arriving at Actaeon Reef within 3 days in (a) early January 2015; and (b) early July 2015. Colours range from areas providing 1-2% (dark blue) to > 10% (dark red).

Application 2: Spread of detritus from cleaning of salmon pens

Our second example relates to the risks associated with cleaning of salmon pens. Pens are cleaned of biofouling using high pressure water blasting. CONNIE can be used to identify the best times to schedule this activity so as to minimize cross-farm or cross-sectoral interactions within the marine environment. Figure 4.10 contrasts the dispersal of dislodged biofouling (one of the options under detritus in CONNIE). At certain times material is retained close to the cages, with potential risks to the caged salmon (Figure 4.10a). Whereas at other times material is carried further upstream along the Huon Estuary, with potential risks to other leases and/or coastal habitats (Figure 4.10b). The dispersal model allows such trade-offs to be identified and managed more effectively.



(a) (b)

Figure 4.10: Comparison of the fate of modelled biofouling originating from cleaning of salmon cages near the mouth of the Huon Estuary at different times: (a) example of high retention around the cages; and (b) example of transport further up the estuary.

Application 3: Spread of Pacific Oyster Mortality Syndrome (POMS)

In late January 2016 the virus associated with Pacific Oyster Mortality Syndrome (POMS) was detected in Tasmanian waters (Lower Pitt Water) for the first time. Over summer it caused major losses in at least six lease areas (dpipwe.tas.gov.au/poms). Subsequent testing of frozen samples indicated that the virus arrived sometime between March and December 2015. Biosecurity Tasmania approached the INFORMD2 team with questions on potential movements of the infection within Tasmanian waters. A large number of scenarios were run using CONNIE and the model was made directly available to Biosecurity Tasmania with the additional inclusion of POMS as one of the preloaded organism options.

In its simplest form, the exposure probabilities generated by CONNIE (P_C) can be related to the probability of infection (P_I) as follows. If we equate an infected farm with a single source cell in CONNIE, then P_C in any geographic cell is the fraction of all the contaminated mucus produced by that farm that passed through that cell. If a second farm only requires a fraction F of the mucus to become infected, then:

$$P_I = P_C / F$$

While it might be quite difficult to estimate F, it is clearly a small number so that $P_I >> P_C$. For example, if we assume $F = 0.01$ (i.e. a farm becomes infected if it receives 1% of the infected mucus from another farm), then cells with CONNIE probabilities > 0.001 have > 10% chance of infection. So even some of the very small probabilities produced by CONNIE may represent a significant infection risk.

Two examples are provided here addressing the questions of whether the virus could have first arrived through the Hobart Port and possible pathways into the D'Entrecasteaux Channel. Results suggest that direct dispersal from Hobart Port could have been responsible for infections of oyster growing areas in Pipe Clay Lagoon (near Clifton Beach), and possibly Pitt Water and Island Inlet (near Sorell) (Figure 4.11a). Areas in the D'Entrecasteaux Channel, such as southern Great Bay, are unlikely to have been infected directly from Hobart Port (Figure 4.11b). However, the presence of wild pacific oyster populations would have allowed the virus to spread through a series of infections.

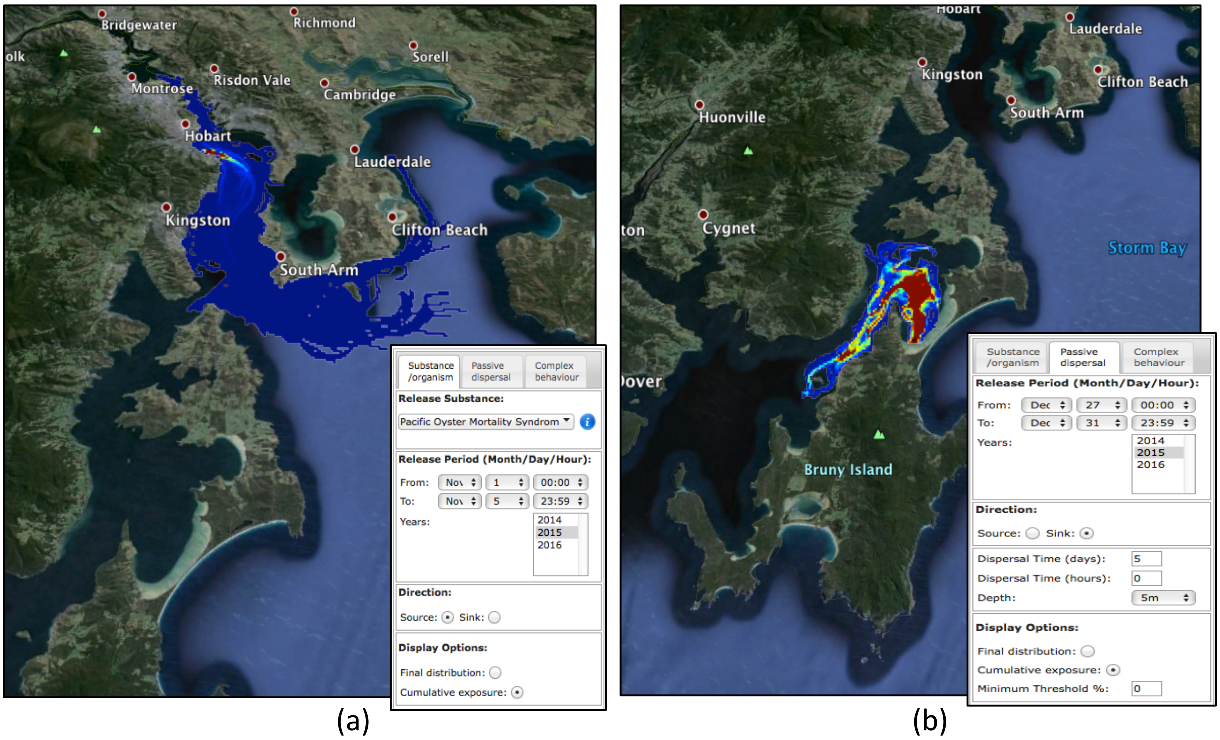


Figure 4.11: Modelled scenarios for the dispersal of POMS including model parameters (inset). (a) Dispersal from Hobart Port in early November 2015. (b) Upstream sources of water arriving in the southern end of Great Bay in late December 2015. In these examples KML files were generated in CONNIE3 before being visualized in Google Earth.

4.4 MAREE

In this section we describe results of the statistical analyses underlying MAREE. We then describe a number of real-world applications of MAREE relevant to the aquaculture industry.

Flow states and climate regimes

The Principal Component Analysis (PCA) of flow states found that approximately 81% of the cumulative proportion of variance was explained by the first two principal components. The associated bi-plot indicated that wind speed and river flow were tightly clustered, while wind direction was clustered away from them with more variability (Figure 4.12). However, it further suggests that most of the states previously identified (Williams et al., 2014) cannot be clearly delineated just in terms of wind and river discharge. Rather, only two states can be resolved: State 1 corresponding to conditions in which one or both of the first two principal components is negative (A, B, C, D, E, F and part of G); and State 2 in which both principal components are positive (H, I and the remainder of G) (Table 3.4). When compared to examples from Williams et al., (2014) we see that the states that we have combined have similar circulation patterns that vary mainly in the strength of the circulation, while state G represents a transition between our States 1 and 2 (Figure 4.12).

Having established that wind and river discharge can clearly delineate two dominant states we have extended this analysis to identify how frequently each state has occurred over the past 7-years. Results based on our 10-day analysis window indicate that the balance of states over the years 2011 to 2015 were all within 5% of the average, while State 1 was anomalously high in 2009 and anomalously low in 2010 (Figure 4.13a). The average of 64% in State 1 and 36% in State 2 was used to define recent climate conditions in MAREE; with an increase in State 2 to 72% in the near-future climate and 100% for the far-future climate (Figure 4.13b).

These three climate conditions can be combined with the four background nutrient loads to give 12 combinations spanning historical and expected future conditions. Under any combination of these conditions, a user can rapidly explore the influence of new or proposed activities that discharge nutrients into the marine environment.

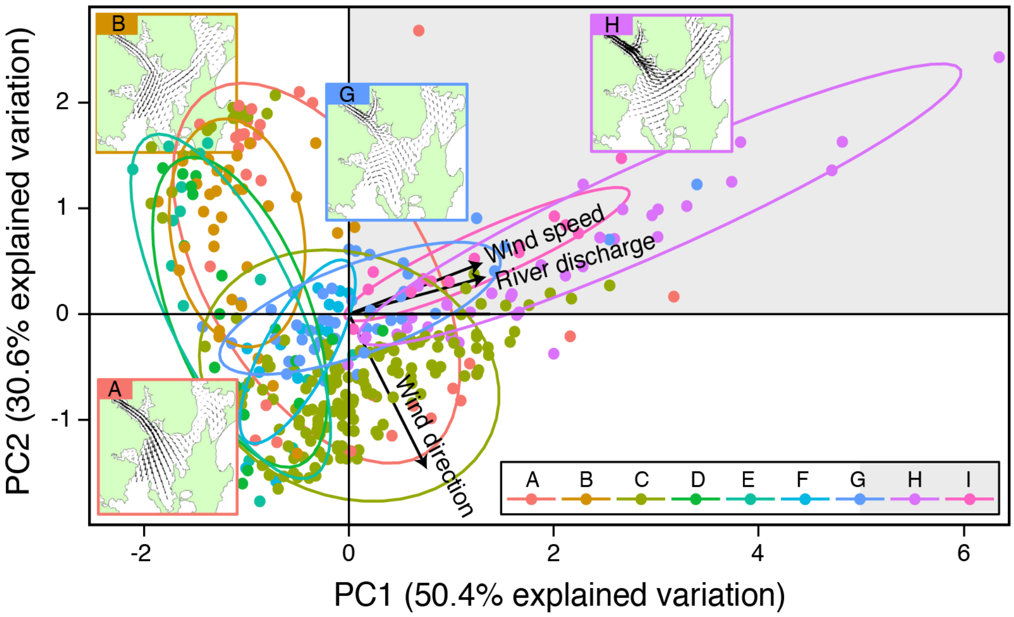


Figure 4.12: Centroid bi-plot of the first two principal components of the PCA based on wind and river discharge conditions from a 12-month period (1 March 2008 to 28 February 2009). The circulation states (A to I in Table 3.4) identified by Williams et al., (2014) are colour-coded with examples from four of those states shown as maps of surface current vectors (also colour coded).

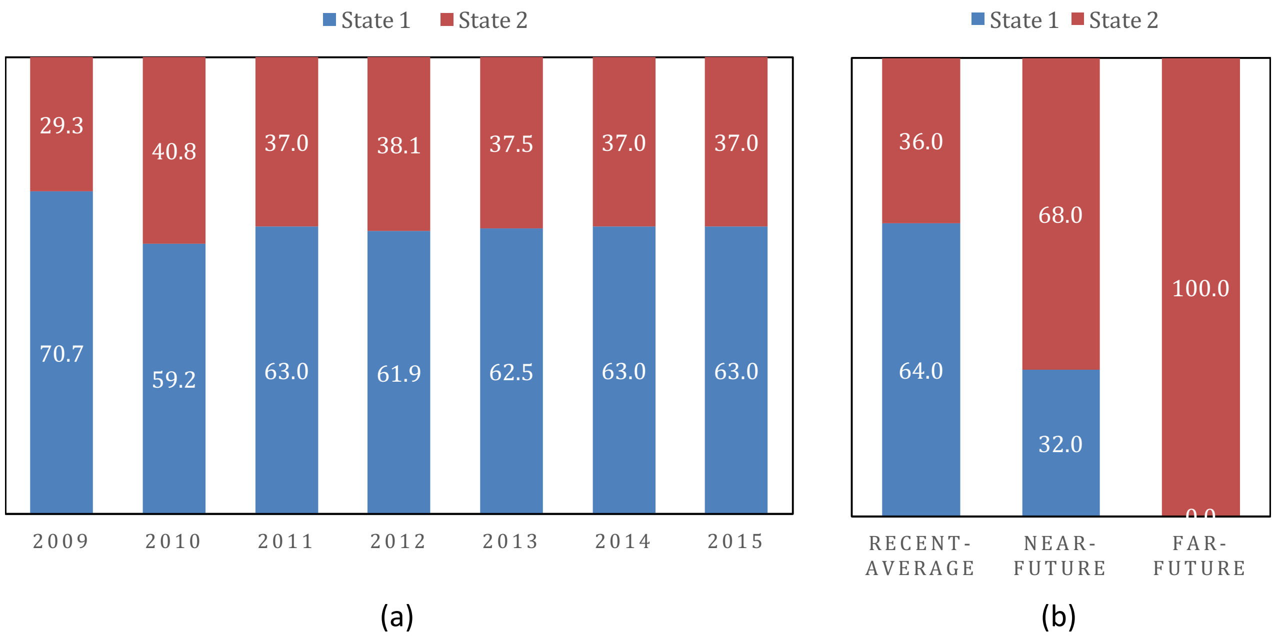


Figure 4.13: (a) Percentages of time that the system is in State 1 or State 2 for each year from 2009 to 2015 based on wind and river discharge conditions and the PCA regimes. (b) Average percentages in each state over these years (recent-average) and percentages assumed for near-future and far-future scenarios.

Representing uncertainty

Uncertainties in the MAREE estimates are represented by error bars computed using Equation 3.4 (Box 3.1). This provides a consistent estimate across all VMSs and was found to cover 98.3% of the BGC model results (Figure 4.14).

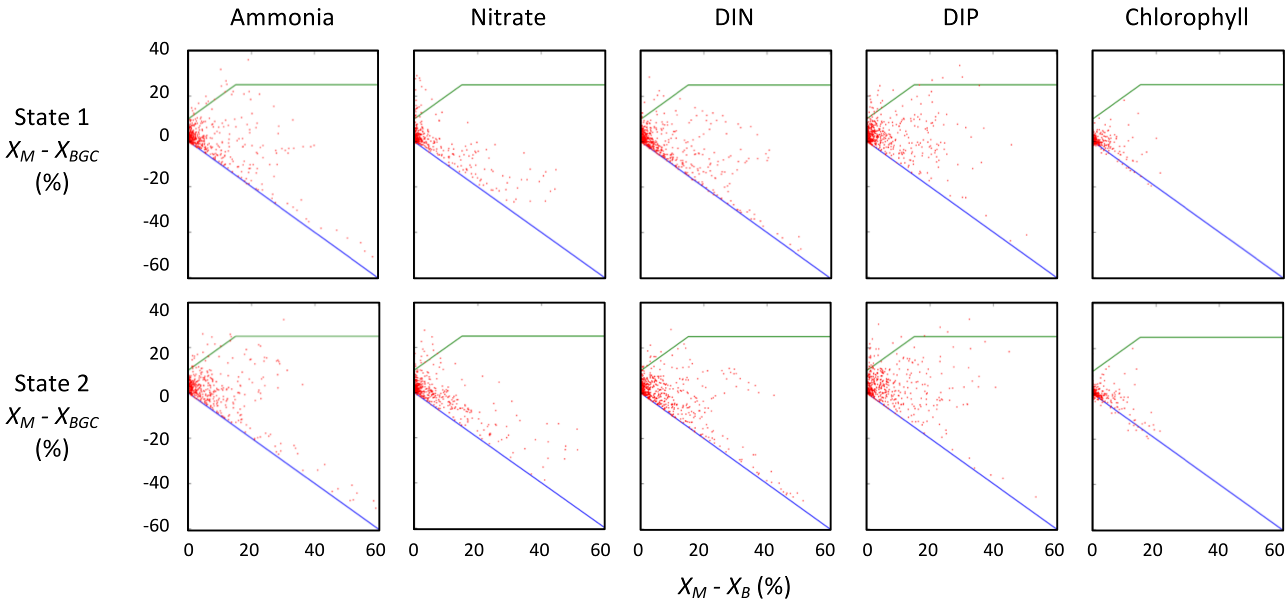


Figure 4.14: Errors in exceedance estimates relative to the BGC model for all nutrients and chlorophyll for State 1 (upper row) and State 2 (lower row). The two solid lines are the same in all cases and encapsulate 98.3% of the data and have been used as the upper and lower error estimates in MAREE.

Application 1: Climate effects on background conditions in the Huon and D'Entrecasteaux Channel

In this example we compare background nutrient levels (i.e. no additional point sources of nutrients) under current and future climate flow scenarios. The only notable change is slightly higher exceedance levels in the Huon Estuary (cf. 4.15a and 4.15b). While this particular scenario did not include changes in riverine nutrient loads, these can be readily specified by a user to generate more comprehensive climate change projections (see below).

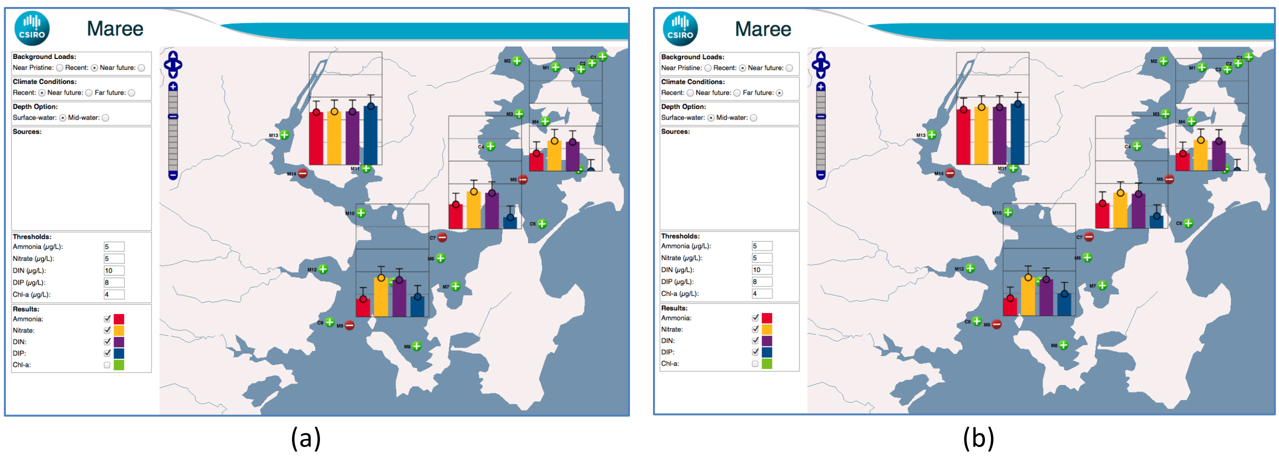


Figure 4.15: Comparison of exceedances at four locations in the Huon Estuary and D'Entrecasteaux Channel under (a) recent climate conditions; and (b) far-future climate conditions. Note that the two cases differ in flows, but not in riverine or point source nutrient loads.

Application 2: Effects of changing aquaculture loads in the Huon and D'Entrecasteaux Channel

In this example we compare nutrient exceedance levels under the three background nutrient loads (near pristine, recent and near future). Not surprisingly, there is a substantial increase in exceedance rates when moving from near pristine to recent loads (cf. 4.16a and 4.16b). This is most evident in ammonia, reflecting the introduction of salmon aquaculture loads. Projected near future loads assume a limited transfer of salmon aquaculture from the Huon into the southern Channel. MAREE results suggest that this change will result in a significant decrease in Huon exceedances with a modest increase at the southern end of the channel (cf. 4.16b and 4.16c).

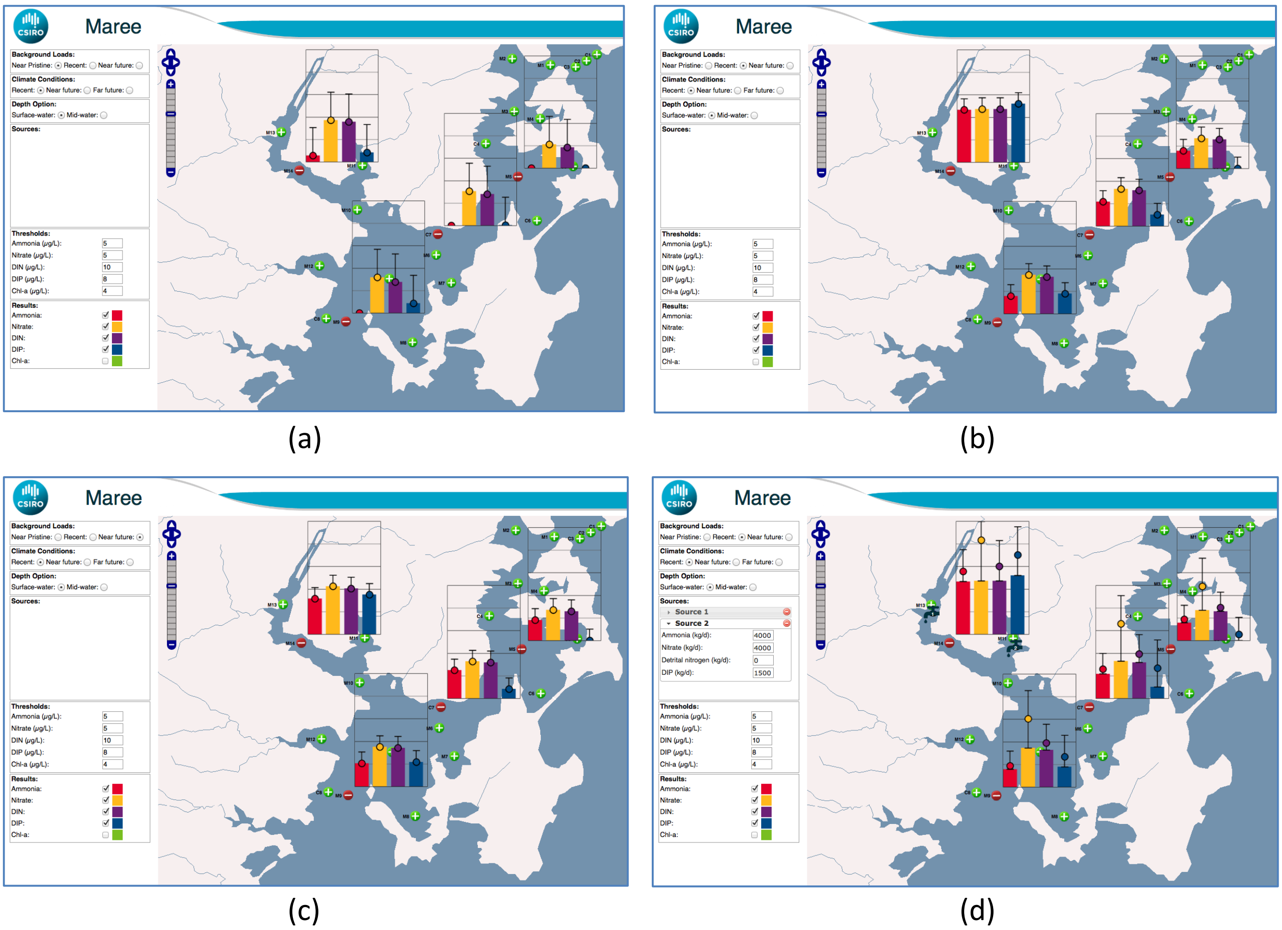


Figure 4.16: Comparison of exceedances at four locations in the Huon Estuary and D'Entrecasteaux Channel with (a) near-pristine conditions; (b) recent background loads; (c) near-future background loads; and (d) recent background loads plus user-specified loads nominally from the Huon catchment.

Application 3: Effects of changing land-use in the Huon Valley

In this example, we add two new nutrient sources in the lower Huon without changing the background loads. This represents a hypothetical change in land-use, such as increased cultivation and fertiliser application. The increased nutrient loads caused a substantial rise in the exceedances of all nutrients that extended beyond the Huon into both the southern and northern channel (cf. 4.16b and 4.16d). The magnitude of these changes is clearly dependent on the specification of source loads and exceedance thresholds.

5. Discussion

The focus of INFORMD2 has been the development of innovative frameworks, models and decision support tools for the southern Tasmanian coastal marine environment. This has included supporting their adoption by government, industry and the community to help manage aquaculture and other coastal and marine industries sustainably (Figure 3.1). Both the development and adoption phases have been very successful.

The YMV process identified many common values across the major stakeholder groups, which helped increase the level of trust and establish a shared understanding of ongoing priorities (Ogier and Macleod 2013). Some of the key priorities were water quality and other local area impacts, and these were subsequently chosen as the focus for development of models and decision support tools.

The BGC modelling was built on the foundation of previous experience and model development in the Huon Estuary Study (CSIRO Huon Estuary Study Team 2000) and the Derwent Estuary Modelling Study (Skerratt et al., 2013, Wild-Allen et al., 2013), as well as elsewhere in Australia (http://www.emg.cmar.csiro.au/www/en/emg/projects.html). The INFORMD2 implementation incorporated a broader range of processes than previously available and expanded the geographical coverage to include both the Derwent and Huon/Channel systems. There was also a strong focus on model calibration and validation (Wild-Allen & Andrewartha, 2016).

The CONNIE decision support system has been implemented for many marine environments in Australia and internationally. New developments for the southern Tasmanian region support preloaded behaviours for substances and organisms based on the best available information. This was identified as a high priority for the aquaculture industry and aimed to minimise the potential for inappropriate parameter selection by non-expert users and provide standardised analyses to support regulatory processes.

Emulators (sometimes referred to as surrogate models or meta-models) have become popular in fields such as water resource modelling where they are used for prediction, design optimisation, sensitivity analysis and uncertainty analysis (Razavi et al., 2012). However, the use of emulators for BGC models have been largely focused on optimising BGC model parameters (Leeds *et al.*, 2013; Hemmings *et al.*, 2015). The MAREE model is the first to focus on scenario modelling for decision support. By making scenario modelling available to a much larger group of managers and regulators, it is helping to realise the full potential of BGC modelling in ensuring the sustainable management of southern Tasmanian coastal waters.

The requirement for extremely rapid generation of online results in CONNIE and MAREE imposes some limitations on the accuracy and coverage of results. For example, while CONNIE provides many options for the behaviour of dispersing substances and organisms, it does not explicitly include the vertical component of water movement and therefore cannot capture the direct influence of upwelling and downwelling flow. In many instances parameterisation of the behaviours themselves is also highly uncertain due to both limitations in empirical data and complexities in the underlying biophysical processes. For instance, CONNIE can represent the dispersal of suspended sediment but not resuspension or bedload transport.

In the case of MAREE, the form of the outputs is restricted to exceedances for key indicators of water quality at a limited number of virtual monitoring sites. They are also based on a limited range of background loading and climate conditions. Hence, if the user wishes to explore the effect of perturbing the system beyond this range, they need to utilise to the original BGC model. The results of any new BGC model runs can be used to expand the range of MAREE scenarios.

The philosophy behind the development of the CONNIE and MAREE decision support tools was to make information immediately available in a format and at a level of detail sufficient for robust decision-making. This approach has the additional advantage that information is delivered at a small fraction of previous costs. As a scenario exploration environment, these tools also provide an opportunity for regulators, industry and community members to use a common methodology to gain a better understanding of how their waterways respond to potential changes in industry and conservation management.

Uptake of the project outputs has been immediate and widespread, reflecting the strong demand for targeted information to support environmental risk assessment. A number of examples have been described including potential for interactions between salmon farming and abalone fisheries, potential impacts of moving salmon production from the Huon into the and D'Entrecasteaux Channel, and understanding the spread of the POMS virus.

Perhaps even more significantly, the Tasmanian Government (through DPIPWE and the EPA) have adopted the BGC model, CONNIE and MAREE as key inputs into their planning, assessment and regulation processes. In supporting environment impact assessments for a major expansion of salmon aquaculture into Storm Bay, the regulator has used these tools to undertake an independent assessment of the potential cumulative impact of proposals from three companies and provided the results back to the companies for inclusion in their own Environmental Impact Statements.

The suite of tools developed within INFORMD2 have significant potential for further development and application. From the perspective of Tasmanian aquaculture, expansion in geographical coverage to include Storm Bay, the East Coast and Macquarie Harbour is a high priority. Salmon aquaculture is expanding in these regions and experiencing environmental pressures, such as toxic algal blooms and low dissolved oxygen, as well as significant community concerns about environmental impacts and sustainability. Hydrodynamic models exist or are under development for all of these regions and CONNIE already covers the Storm Bay area. However, the BGC model and MAREE are currently restricted to the Derwent-Huon-D'Entrecasteaux region. Expanded coverage of BGC modelling (running in near-real time) would provide a stepwise increase in the quantity and quality of environmental information accessible to both industry and regulators. This advance would not only contribute to industry sustainability, but could also underpin their social license to operate (SLO).

Implications

INFORMD2 represents a fundamental advance in our ability to undertake environmental risk assessments that include elements such cumulative, nonlinear and threshold effects to address regional-scale social, economic and environmental issues. In the context of southern Tasmanian marine environment, this includes assessing the impacts of changes in discharges from sewage or industrial facilities, new aquaculture leases or changes in stocking rates of existing leases, and changes in catchment land uses. Importantly, these tools not only improve the effectiveness of these assessments, but also the efficiency with which they can be carried out. This is of particular value where industries or regulators need to undertake preliminary assessments as part of a screening process or a staged approval process.

The capabilities provide through INFORMD2 support testing of alternative management strategies and regulatory frameworks, including potential for off-setting increases in nutrient loads in one sector with reductions in another sector. Within the CONNIE and MAREE frameworks alternative strategies can be rapidly specified and compared by a non-expert operator. Importantly, the immediacy of results provides an effective learning environment for managers and other stakeholders to gain an improved and shared understanding of how the system responds to alternative management actions.

The INFORMD2 risk-based management tools can also help to reduce the potential for conflict between users of the marine system. A shared understanding of the values held by all stakeholder groups, as provided by YMV, is clearly central to this goal. Furthermore, many conflicts are based around perceived risks and the ability to address concerns quickly and cheaply with online tools will allow managers to focus on issues that pose significant and quantifiable risks. Over the longer term, the availability of such technologies will also support for changes in formal assessment processes aimed at reducing costs and approval times for some types of activities and developments.

Recommendations

Specific recommendations for further application or development of the approaches developed within INFORMD2 include:

i. Government and industry may like to consider how the suite of approaches and tools developed within INFORMD2 could further assist in their approval or management processes, and whether any further refinements are required to realise such benefits.

ii. Using the YMV process, INFORMD2 identified a comprehensive set of marine environmental values. However, there was not scope within the project to properly understand and articulate the links between Tasmanian aboriginal values and other marine values. This has been identified as an important area requiring further investigation.

iii. While CONNIE is maintained in near real-time by CSIRO, the biogeochemical model is currently applied ad hoc to specific historical periods or scenarios to meet the needs of individual projects. This is an inefficient approach to providing biogeochemical modelling capability as the model needs to be manually updated for each new application. It is therefore recommended that the biogeochemical model be run in near real-time using available data streams for model forcing and ongoing validation. This approach will generate an expanding archive of historical conditions and ensure that a state-of-the-art biogeochemical model is always available for generating scenarios and testing management strategies.

iv. The planned expansion of salmon aquaculture into Storm Bay presents significant opportunities and risks. CONNIE already covers this region at relatively high resolution and has been adopted as part of the government planning process for assessing environmental risks and designing an effective monitoring program. However, early application of the YMV approach could help manage perceptions and expectations, thereby reducing the potential for conflicts over the longer term. Extension of the biogeochemical model into Storm Bay would provide a cost effective approach to extrapolating limited historical observations and thereby provide much of the environmental information needed to monitor and manage the system effectively. Extension of the MAREE decision support tool into Storm Bay would provide a corresponding risk assessment capability directly to government and industry.

v. All of the models and tools developed within INFORMD2 are potentially deployable to other regions to support environmental risk assessment, management and conflict resolution. In the context of salmon aquaculture, there may be significant benefits in developing comparable capabilities in Macquarie Harbour on the west coast of Tasmania with a specific focus on dissolved oxygen issues.

Extension and adoption

The Project Advisory Committee, with membership from government, industry peak bodies, aquaculture companies and the research community, has proven to be a very effective forum for communicating the progress and outcomes of INFORMD2. Regular meetings and small workshop with this group have contributed to both refinement of the project products and their subsequent adoption.

A series of small informal workshops have been conducted with the Tasmanian Government (DPIPWE and EPA), Regional Partnerships (Derwent Estuary Program and D'Entrecasteaux and Huon Collaboration), and Huon Aquaculture and Tassal, with a focus on training individuals within those organisations to use CONNIE and MAREE for their specific needs. A similar workshop has also been planned with Petuna. These workshops typically involved a short background presentation on the scientific rationale, followed by live demonstrations. The third and largest part of each workshop was devoted to using the tools to explore issues of immediate concern to the participating stakeholder group. Participants were also invited to approach the development team at any time in the future to clarify issues or obtain further advice and assistance in running the online tools.

Examples of adoption of project outputs to date include:

i. Modelling system responses to changes in stocking rates of existing leases (DPIPWE).

ii. Estimating the risk of salmon aquaculture in the D'Entrecasteaux Channel directly impacting on abalone reefs (TSGA).

iii. Assessment of potential interactions between proposed lease sites and other marine assets in Storm Bay and designing an effective monitoring program for the region (DPIPWE, ongoing).

iv. Estimating the risks of Pacific Oyster Mortality Syndrome (POMS) moving between lease sites in southern Tasmania (Biosecurity Tasmania, ongoing).

v. CONNIE has recently been adopted as the agreed standard for generating information on dispersal for Environmental Impact Statements relating to aquaculture in southern Tasmania. In the context of proposed new leases in Storm Bay, this new arrangement has provided relevant information in a timely manner, with substantially reduced costs to the aquaculture industry.

Project coverage

The YMV component of the project was advertised via television and radio interviews, articles in local newspapers, a purpose designed website with links to other relevant organisational websites, a Facebook page and posters printed and distributed widely in the focus areas. Communication of other aspects of the study has targeted government, industry and the scientific community through workshops and presentations at conferences.

Communications undertaken to date include:

- Presentation to the regional partnership groups: Derwent Estuary Program and D'Entrecasteaux and Huon Collaboration (S. Condie, K. Wild-Allen, March 2017)
- Presentations (x2) at the mini conference: Our Waterway, Hobart (S. Condie, K. Wild-Allen, August 2016)
- Presentation at the conference: Understanding marine socio-ecological systems: including the human dimension in Integrated Ecosystem Assessments, Brest, France (R. Little, June 2016).
- Presentation at the South Australian Research and Development Institute (S. Condie, March 2016)
- Presentation at MODSIM conference, Gold Coast (R. Little, December 2015)
- Presentation at Transdisciplinary Interdisciplinary Integrated Science (TIIS) workshop (May 2015)
- Presentation at the European Conference on Ecological Modelling (K. Wild-Allen, October 2014).
- Presentation at the World Aquaculture Society Conference, Adelaide (E. Ogier, June 2014)
- Presentation at the Advances in Marine Ecosystem Modelling Research conference, Plymouth, UK (S. Condie, June 2014)
- Article in Fishing Today (December/January 2014)
- Article in Fishing Today "Your Marine Values: workshop and survey" (February/March 2013)
- TV interview with Southern Cross Television (C. Macleod & E. Ogier, 30th January 2013)
- Radio Interview with the Country Hour, Tasmania (S. Condie & C. Macleod, Dec 2012)
- Radio Interview with the Tasmanian Drive (S. Condie, Dec 2012)
- Article in Kingborough Chronicle, Huon Valley Times, UTas Bulletin, (Feb 2012)
- Website http://www.imas.utas.edu.au/research/fisheries/frdc/stage-2-informd
- Facebook page http://www.facebook.com/YourMarineValues

Project materials developed

Publications to date

Hadley, S., Wild-Allen, K., Johnson, C. & Macleod, C. (2015) Modeling macroalgae growth and nutrient dynamics for integrated multi-trophic aquaculture. Journal of Applied Phycology, 27, 901-916.

Hadley, S., Wild-Allen, K., Johnson, C. & Macleod, C. (2016a) Quantification of the impacts of finfish aquaculture and bioremediation capacity of integrated multi-trophic aquaculture using a 3D estuary model. Journal of Applied Phycology, 28, 1875-1889.

Hadley, S., Jones, E., Johnson, C., Wild-Allen, K. & Macleod, C. (2016b) A Bayesian inference approach to account for multiple sources of uncertainty in a macroalgae based integrated multi-trophic aquaculture model. Environmental Modelling & Software, 78, 120-133.

Ogier, E. & Macleod, C. K. (2013) Your Marine Values – Public Report. 2013 online version. IMAS Technical Report 120pp. University of Tasmania. ISBN 978-1-86295-930-9 (http://www.imas.utas.edu.au/__data/assets/pdf_file/0010/743356/Your-Marine-Values-Document_WEB-FULL.pdf).

Wild-Allen, K. & Andrewartha, J. (2016) Connectivity between estuaries influences nutrient transport, cycling and water quality. Marine Chemistry (In Press) doi:10.1016/j.marchem.2016.05.011

Software

The Marine Ecological Emulator (MAREE) was developed as part of the project.

Appendix A: Researchers and other project contributors

Project Team

CSIRO:

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Tassal Group

Matt Barrenger

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Appendix B: Intellectual Property

The intellectual property arising from the INFORMD2 research is the property of CSIRO, the University of Tasmania and the FRDC.

The hydrodynamic model, biogeochemical model, and CONNectivity InterfacE (CONNIE3) all existed prior to the INFORMD2 project and remain the property of CSIRO.

The MARine Ecological Emulator (MAREE) was developed as part of the INFORMD2 project and is the property of CSIRO and FRDC.

Appendix C: Project objectives and related outcomes

In relation to the specific objectives identified at the beginning of the project, the results can be summarised as follows:

i. **In relation to aquaculture and the marine environment of southern Tasmania, characterise key economic, social and environmental values and aspirations from industry, government and community perspectives.**

   This was achieved through the series of workshops with government, industry and community groups that successfully identified key values. These values were validated with stakeholders and collated into a structured framework spanning environmental, economic and social values across the key stakeholder groups. The results from this aspect of the study have been broadly distributed in the "Your Marine Values" Public Report (Ogier and Macleod 2013; Figure 3.1a).

ii. **Relate these values qualitatively to measurable indicators based on an understanding of key biophysical and socio-economic processes.**

   This objective was achieved by identifying relationships to measureable indicators and known monitoring in the last of the YMV workshops involving all stakeholder groups, with additional input from scientific experts. The project team then identified those values, indicators and types of scenarios that could be incorporated into the models and risk-based decision support tools.

iii. **Develop a framework to support spatial risk assessment for planning of future development within the context of other natural processes and anthropogenic activities within the system, with an initial focus on aquaculture leases.**

   This objective was achieved by development of a new regional biogeochemical model (Figure 3.1b) and the risk-based decision support tools CONNIE (Figure 3.1c) and MAREE (Figure 3.1d). Each of these products can be used to test the marine environmental impacts of development scenarios for aquaculture and other coastal and marine industries. They can support a staged approach with rapid low-cost assessments based on CONNIE and/or MAREE potentially triggering more detailed assessments using tools such as the biogeochemical model.

iv. **Develop a framework for developing and evaluating spatial risk management strategies, with an initial focus on managing within and across aquaculture leases.**

   This objective was achieved through the strategy outlined under objective (iii), as each of these tools allows specific management strategies to be represented and tested.

v. **Integrate the planning framework (objective iii) and risk management framework (objective iv) into an online tool accessible to stakeholders.**

   This objective has been achieved through the development of the online tools CONNIE (dispersal and connectivity) and MAREE (water quality impacts). CONNIE is publicly available (www.csiro.au/connie/), while MAREE is available to government and the aquaculture industry.

Appendix D: Preloaded substances

The following substances types have been parameterised and loaded into CONNIE.

Sediments - silt

Settling rate:	10 m/day
Total Dispersal Duration:	8 days, 13 hours
Display Minimum Threshold:	0.0%
Phase 1:	2 hours @ 1 m
Phase 2:	5 hours @ 2 m
Phase 3:	10 hours @ 5 m
Phase 4:	12 hours @ 10 m
Phase 5:	22 hours @ 15 m
Phase 6:	36 hours @ 28 m
Phase 7:	53 hours @ 45 m
Phase 8:	65 hours @ 72 m

Reference:
Condie SA and Sherwood CR. 2006. Sediment distribution and transport across the continental shelf and slope under idealized wind forcing. Prog Oceanogr 70: 255-270 included in the style.

Sediments - coarse silt or very fine sand

Settling rate:	100 m/day
Total Dispersal Duration:	18 hours
Display Minimum Threshold:	0.0%
Phase 1:	1 hour @ 5 m
Phase 2:	1 hour @ 10 m
Phase 3:	2 hours @ 15 m
Phase 4:	4 hours @ 28 m
Phase 5:	5 hours @ 45 m
Phase 6:	5 hours @ 72 m

Reference:
Condie SA and Sherwood CR. 2006. Sediment distribution and transport across the continental shelf and slope under idealized wind forcing. Prog Oceanogr 70: 255-270 included in the style.

Sediments - fine sand

Settling rate:	500 m/day
Total Dispersal Duration:	3 hours
Display Minimum Threshold:	0.0%
Phase 1:	1 hours @ 28 m
Phase 2:	1 hour @ 45 m
Phase 3:	1 hour @ 72 m

Reference:
Condie SA and Sherwood CR. 2006. Sediment distribution and transport across the continental shelf and slope under idealized wind forcing. Prog Oceanogr 70: 255-270.

Detritus - zooplankton carcasses

Settling rate:	100 m/day
Total Dispersal Duration:	18 hours
Display Minimum Threshold:	1.0%
Phase 1:	1 hour @ 5 m
Phase 2:	1 hour @ 10 m
Phase 3:	2 hours @ 15 m
Phase 4:	4 hours @ 28 m
Phase 5:	5 hours @ 45 m
Phase 6:	5 hours @ 72 m

Reference:
Kirillin G, Grossart HP and Tang KW. 2012. Modelling sinking rate of zooplankton carcasses: Effects of stratification and mixing. Limnol Oceanogr 57: 881-894.

Detritus - marine snow

Settling rate:	100 m/day
Total Dispersal Duration:	18 hours
Display Minimum Threshold:	1.0%
Phase 1:	1 hour @ 5 m
Phase 2:	1 hour @ 10 m
Phase 3:	2 hours @ 15 m
Phase 4:	4 hours @ 28 m
Phase 5:	5 hours @ 45 m
Phase 6:	5 hours @ 72 m

Reference:
Diercks A-R, Asper VL. 1997. In situ settling speeds of marine snow aggregates below the mixed layer: Black Sea and Gulf of Mexico. Deep Sea Res I 44: 385-398.

Detritus - fish faeces

Settling rate:	100 m/day
Total Dispersal Duration:	18 hours
Display Minimum Threshold:	1.0%
Phase 1:	1 hour @ 5 m
Phase 2:	1 hour @ 10 m
Phase 3:	2 hours @ 15 m
Phase 4:	4 hours @ 28 m
Phase 5:	5 hours @ 45 m
Phase 6:	5 hours @ 72 m

Reference:
Reid GK, Liutkus M, Robinson SMC, et al., 2009. A review of the biophysical properties of salmonid faeces: Implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. Aquac Res 40: 257-273.

Detritus - dislodged biofouling

Settling rate: 500 m/day
Total Dispersal Duration: 3 hours
Display Minimum Threshold: 1.0%
Phase 1: 1 hours @ 28 m
Phase 2: 1 hour @ 45 m
Phase 3: 1 hour @ 72 m

Reference:
Flindt MR, Pedersen CB, Amos CL, Levy A, Bergamasco A, Friend PL. 2007. Transport, sloughing and settling rates of estuarine macrophytes: Mechanisms and ecological implications. Cont Shelf Res 27: 1096-1103.

Debris - mostly submerged object (24 hours, 48 hours, 7 days)

Settling rate: 0 m/day
Total Dispersal Duration: 1, 2 or 7 days
Display Minimum Threshold: 0.0%
Phase 1: 1, 2 or 7 days @ 1 m + 1% windage

Reference:
Kako S, Isobe A, Yoshioka S, Chang P, Matsuno T, Kim S, Lee J. 2010. Technical issues in modelling surface drifter behaviour on the East China Sea Shelf. J Oceanogr 66:161-174.

Debris - partially submerged object (24 hours, 48 hours, 7 days)

Settling rate: 0 m/day
Total Dispersal Duration: 1, 2 or 7 days
Display Minimum Threshold: 0.0%
Phase 1: 1, 2 or 7 days @ 1 m + 3% windage

Reference:
Kako S, Isobe A, Yoshioka S, Chang P, Matsuno T, Kim S, Lee J. 2010. Technical issues in modelling surface drifter behaviour on the East China Sea Shelf. J Oceanogr 66:161-174.

Debris - mostly emerged object (24 hours, 48 hours, 7 days)

Settling rate: 0 m/day
Total Dispersal Duration: 1, 2 or 7 days
Display Minimum Threshold: 0.0%
Phase 1: 1, 2 or 7 days @ 1 m + 5% windage

Reference:
Kako S, Isobe A, Yoshioka S, Chang P, Matsuno T, Kim S, Lee J. 2010. Technical issues in modelling surface drifter behaviour on the East China Sea Shelf. J Oceanogr 66:161-174.

Oil – diesel oil (24 hours, 48 hours, 7 days)

Settling rate:	0 m/day
Total Dispersal Duration:	1, 2 or 7 days
Display Minimum Threshold:	1.0%
Phase 1:	1, 2 or 7 days @ 1 m + 3% windage
Decay time:	1 day

Reference:
Chao XB, Shankar NJ and Cheong HF. 2001. Two- and three-dimensional oil spill model for coastal waters. Ocean Eng 28:1557-1573.
Trajectory Analysis Handbook
(http://response.restoration.noaa.gov/sites/default/files/Trajectory_Analysis_Handbook.pdf).

Oil - light crude oil (24 hours, 48 hours, 7 days)

Settling rate:	0 m/day
Total Dispersal Duration:	1, 2 or 7 days
Display Minimum Threshold:	1.0%
Phase 1:	1, 2 or 7 days @ 1 m + 3% windage
Decay time:	4 days

Reference:
Chao XB, Shankar NJ and Cheong HF. 2001. Two- and three-dimensional oil spill model for coastal waters. Ocean Eng 28:1557-1573.
Trajectory Analysis Handbook
(http://response.restoration.noaa.gov/sites/default/files/Trajectory_Analysis_Handbook.pdf).

Oil - heavy crude oil (24 hours, 48 hours, 7 days)

Settling rate:	0 m/day
Total Dispersal Duration:	1, 2 or 7 days
Display Minimum Threshold:	1.0%
Phase 1:	1, 2 or 7 days @ 1 m + 3% windage
Decay time:	9 days

Reference:
Chao XB, Shankar NJ and Cheong HF. 2001. Two- and three-dimensional oil spill model for coastal waters. Ocean Eng 28:1557-1573.
Trajectory Analysis Handbook
(http://response.restoration.noaa.gov/sites/default/files/Trajectory_Analysis_Handbook.pdf).

Appendix E: Preloaded organisms

The following organism types have been parameterised and loaded into CONNIE.

Plankton – large diatom chains

Settling rate:	5 m/day
Total Dispersal Duration:	16 days
Display Minimum Threshold:	1.0%
Phase 1:	5 hours @ 1 m
Phase 2:	10 hours @ 2 m
Phase 3:	19 hours @ 5 m
Phase 4:	24 hours @ 10 m
Phase 5:	43 hours @ 15 m
Phase 6:	72 hours @ 28 m
Phase 7:	106 hours @ 45 m
Phase 8:	105 hours @ 72 m

Reference:
Passow U. 1991. Species-specific sedimentation and sinking velocities of diatoms. Marine Biology, 108, 449-455.

Plankton – large diatom aggregates

Settling rate:	100 m/day
Total Dispersal Duration:	18 hours
Display Minimum Threshold:	1.0%
Phase 1:	1 hour @ 5 m
Phase 2:	1 hour @ 10 m
Phase 3:	2 hours @ 15 m
Phase 4:	4 hours @ 28 m
Phase 5:	5 hours @ 45 m
Phase 6:	5 hours @ 72 m

Reference:
Passow U. 1991. Species-specific sedimentation and sinking velocities of diatoms. Marine Biology, 108, 449-455.

Virus – Pacific Oyster Mortality Syndrome (POMS)

Settling rate:	0 m/day
Total Dispersal Duration:	4 days
Display Minimum Threshold:	0.0%
Phase 1:	4 days @ 2 m
Mortality time:	0.3 days

Reference:
Hick P, Evans O, Looi R, English C, Whittington RJ. 2016. Stability of Ostreid herpesvirus-1 (OsHV-1) and assessment of disinfection of seawater and oyster tissues using a bioassay. Aquaculture 450: 412-421.

Virus – Pacific Oyster Mortality Syndrome (POMS, assuming high mortality)

Settling rate:	0 m/day
Total Dispersal Duration:	3 days
Display Minimum Threshold:	0.0%
Phase 1:	3 days @ 2 m
Mortality time:	0.1 days

Reference:
Hick P, Evans O, Looi R, English C, Whittington RJ. 2016. Stability of Ostreid herpesvirus-1 (OsHV-1) and assessment of disinfection of seawater and oyster tissues using a bioassay. Aquaculture 450: 412-421.

Virus – Pacific Oyster Mortality Syndrome (POMS, assuming low mortality)

Settling rate:	0 m/day
Total Dispersal Duration:	5 days
Display Minimum Threshold:	0.0%
Phase 1:	5 days @ 2 m
Mortality time:	0.5 days

Reference:
Hick P, Evans O, Looi R, English C, Whittington RJ. 2016. Stability of Ostreid herpesvirus-1 (OsHV-1) and assessment of disinfection of seawater and oyster tissues using a bioassay. Aquaculture 450: 412-421.

Appendix F: Parameterisation of CONNIE3

In order to help with the understanding and comparison of model outputs generated using CONNIE3 the Institute for Marine and Antarctic Studies prepared this summary of:

(i) The parameters that can be varied in CONNIE3, a definition of each parameter and an explanation of requirements and things to be aware of when using CONNIE3 for assessment of nutrient dispersion.
(ii) IMAS specific parameterisation of the CONNIE3 model; to simulate dispersion of dissolved nutrients from proposed marine farming sites in Storm Bay in order to inform the design of a monitoring program that would align with proposed development (as outlined by DPIPWE), along with a justification as to why those particular parameters/ constraints were selected, and
(iii) An overview of other considerations for both defining and interpreting CONNIE3 model runs.

(i) The table below outlines the user defined parameterisation options available in CONNIE3.

Parameter	Points To Note
Release period **DEFINITION**: The release period indicates the number of days over which the particles are released. Release period is connected to both dispersal time and decay rate. The release time and dispersal time in combination will define the full period over which the assessment (model) is run - *for example a release time of 14 days, with a dispersal time of 4 days would result in the full model run being 18 days, as any particles released on the last day (up to midnight) would require 4 days to reduce to negligible concentrations*. Release time needs to be representative of the interactions you are considering. A single day release is only representative of dispersal from that day, whereas a more extended release would be needed to establish any longer term dispersal patterns.	• Decisions regarding release time will vary depending on the question/ issue to be addressed and on the particular system – *this may be refined as local knowledge/ system understanding increases*. • The choice of release period will be influenced by both dispersal time and decay rate. To establish a dispersion pattern indicative of the long-term it is important to make sure that the particles are in the system long enough. *For example - if we release for 1 day and disperse for 4-days, then we only really get a sense of the dispersal in the system for those 5 days (which is very dependent on the 4 days you choose). If we release for 2 weeks, and disperse for 4-days, then we get a sense of the dispersal pattern over 18 days, which may be more informative in terms of longer term flow patterns, tidal cycles etc.*
Decay rate **DEFINITION**: Decay Rate is employed to represent an integrated measure of the influence of natural processes other than hydrodynamic transport (e.g. biological uptake, nitrification) on the concentration of particles in the system. In a natural system decay rate can change markedly, both in space and over time. Decay is an exponential process, with the total amount being reduced in the system each day, by a fraction proportional to the decay rate. In the model this reduction is averaged over all particles which were released at the same time, i.e. the model does not randomly remove individual particles, but rather calculates this by fractionally reducing the amount of nutrient represented by each individual particle over time.	• Decay rate will vary depending on i) the nature of the particular outputs (e.g. a particular nutrient, feed, faeces or some other particle) and ii) the system processes (e.g. nutrient dynamics in Storm Bay). • Parameterisation can be based on known empirical data or literature values, a reasoned theoretical understanding of the processes or just a "best guess". However, it should be noted that for assessment of nutrient connectivity any of the biological/chemical 'losses' are dynamic processes that display strong spatial and temporal gradients. • It is worth noting that forcing an actual system with high loads of a relatively conservative particle (e.g. nitrogen) has the potential to saturate the system and the biological processes, resulting in slower decay. • Comparing the effects of different decay rate can be informative - providing a better understanding of the extent to which this parameter can actual change the model output (i.e. a measure of the sensitivity of this parameter in the model) • In an assessment model like CONNIE3 decay rate is constant (spatially and temporally) in the model run, and therefore running the model with different decay rates could be used to explore the potential effect of changes in "natural processes".

Dispersal time

DEFINITION: Dispersal Time defines the number of days the particles disperse once they are released.

Each day of the release time particles are introduced into the system, they are then moved around the system by the hydrodynamics (currents) for the user defined “dispersal time”.

- Where connectivity is being explored, the dispersal time needs to be sufficient for the connectivity to be established. Noting that the connectivity may vary depending on the distance between features of interest (e.g. farms) and with the current regime in the region of interest.
- Where a decay rate is defined, then there is little point making the dispersal time longer than the particle decay time, as concentrations will become negligible after the decay time (e.g. after decay time – there will be only 5% of the particle concentration that there would have been in the absence of decay).
- The specification of dispersal time will be dictated by the particular question being asked - *for example, whether you want to know how far a particle might travel in a specific timeframe or how long it is until a particle reaches the model boundary.*
- A useful test is to compare concentrations using a range of dispersal times; as at some point the distribution will become less sensitive to increases in the dispersal time.

Release depth

DEFINITION: This defines where the particles are released in the water column. All subsequent dispersal occurs at this depth (unless diurnal migration is specified).

CONNIE3 offers release depths of 1, 2, 5, 10, 15, 28, 45 and 72m. Each depth has an associated water current field that is used to push the particles horizontally around the CONNIE grid.

- If the release depth is greater than the local water depth, then particles can’t move.
- Changing the release depth will alter the distribution pattern observed.

Modelled period

DEFINITION: This is the historical period (days, months and years) that the model run is initiated and run over.

- This is user defined, and will be “question” specific.
- It is generally considered important to ensure that the timeframe captures the major modes of the system being modelled - *for example, if hydrodynamics in the system were dominated by river flow (i.e. low river flow meant low circulation in the estuary) it would be important to include periods of both low (high) river flow. Alternatively, if the system shows high seasonal variability then model runs should be conducted in each season. Similarly, capturing tidal influences may be important. Note: that the model itself can be used to identify this variability.*
- Knowledge of the local system is very important in devising potential scenarios and in outlining the modelling period. Previous studies in Storm Bay have provided a good understanding of the mean flows and the magnitudes and directions of residual currents in this region.

(ii) IMAS specific parameterisation for modelling to simulate dispersion of nutrients from proposed salmon farming operations in Storm Bay using CONNIE3:

Parameter (Setting)	Rationale/ Justification for Selected Settings
Release period: 14 days	In this instance 14 days was chosen, as it was felt that this was sufficient to cover the spring-neap tidal cycle and other cycles of synoptic weather systems that influence wind and rainfall.
Decay rate: 4 days	There is no single definition of ammonia decay rate in marine systems. Decay rate will vary depending on local nutrient uptake dynamics, and therefore this parameter needs to be informed by local information. Modelling studies in the Derwent and Huon Estuaries and D'Entrecasteaux Channel have shown that the greatest loss of nitrogen in this system is through denitrification (the process that converts nitrate to nitrogen gas). Results from modelling in these regions (Wild-Allen and Andrewartha 2016, DHD model) suggest that ammonia would appear to be converted to nitrate in the water column at a constant rate of approximately 10% per day. The other major sink for ammonia is phytoplankton uptake, which is highly dynamic (both temporally and spatially). However, if we consider the phytoplankton uptake as having a similar influence on ammonia level to that of water column assimilation, i.e. 10% each, then the cumulative loss would be 20% per day. We also assume 10% of farm derived ammonia (released in the top 15m) is lost to the lower layers, giving a total approximate loss of 30%, which is broadly equivalent to a 4-day decay rate. We have also run the model with both a decay rate of 8-days (in the case that these losses are significantly slower) and no decay to compare the results and provide a better understanding as to the sensitivity of this parameter. We found spatial concentration differences between the 4 and 8-day decay results ranged between 0.5 – 2 mg $\mathrm{N\ m^{-3}}$. A 1-2 day decay rate may be relevant to represent a situation where nutrients are taken up very quickly (e.g. during a phytoplankton bloom). Such a scenario is not representative of typical conditions in Storm Bay; on that basis analysis with a shorter decay rate was deemed inappropriate.
Dispersal time: 4 days	The dispersal time matches the decay-rate used. In this case we selected the longest dispersal time possible, as it was felt that a 4-day dispersal period would provide plenty of time for particles (nutrients) to move between farm sites in Storm Bay, and therefore would definitely show the extent to which nutrient distributions might overlap.
Modelled Period: 4 time periods - 1st July, October (2014) and January, April (2015).	Note: CONNIE3 has capacity to model scenarios in Storm Bay for years 2014 – 2016. The times in this case were selected to capture temporal (seasonal) variation. Note: Assessing the effects of long term inter-annual variations in hydrodynamic dispersal patterns and connectivity would require generation of data specific to that question/ objective. *We did not observe any major seasonal differences in the results. If the results did suggest seasonal changes then it would be useful to assess those patterns over a number of years to establish the level of inter-annual variability.*
Release sites and loads: Existing and proposed sites in the Storm Bay region.	Both input (biomass/ feed) loads and farm locations need to be realistic for each scenario, as these parameters have a significant effect on modelling output. Input loads and farm locations used in this modelling reflect proponent information provided by DPIPWE.

Release depths*: *Depth averaged*: 0-15m & 15-28m *Release weighting*: 100% released in top 15m 1m (25%) 5m (25%) 10m (25%) 15m (25%) 10% of the total amount released into the top 15m is assumed to have been transported into the lower depth (i.e 15-28m) and this has been modelled separately.	When converting particle concentrations to ammonia concentrations (based on farm input loads) it is possible to "weight" the different depth layers independently (this step requires post processing of CONNIE3 output). For example, you can assume equivalent amounts of nutrients are released in each depth category or that more nutrients are released at one depth than another. In the IMAS calculations it was assumed that the same fraction of the total amount of nutrients was released in each depth layer (i.e. 25% of the nutrient load was released in the 1m layer, 25% in the 5m layer, etc). This assumption is based on CSIRO's previous work on salmon farms in the region (Wild-Allen et al., 2010) where nutrients were released evenly in the top 12m. Outputs will be depth averaged concentration gradient maps for 0-15m and 15 -28m for each season modelled.
Concentration Gradient*:	Conversion of particle concentration to ammonia concentration based on load values provided by DPIPWE.

* Results from CONNIE3 runs for these settings have been post processed by IMAS.

(iii) Overview of Other Considerations for both Defining and Interpreting CONNIE3 Model Runs:

- Results should be interpreted with the relevant degree of caution. To fully categorise the state of the system would require further model validation and the observations would need to be tested/confirmed, particularly where these relate to the potential for biological outcomes/ interactions. That said, the estimates of dispersal patterns are realistic as the hydrodynamic patterns in Storm Bay are reasonably well understood and have been derived from environmental forcing that is well represented (Herzfeld, 2010).

- If additional empirical data was available to inform the modelling this could be incorporated into future runs.

- **Decay rate** is used to simulate the combined effect of a number of particle (nutrient uptake) processes and as such this variable has an important influence on the outputs for the CONNIE3 model. Any information that would allow this proxy to be more accurately determined should be carefully considered. Currently, the exponential decay captures the dynamics of loss of nutrients through both chemical and biological processes. However, it is important to note that the overall loss of particles (nutrients) from the system actually includes both the effect of 'decay' and 'dispersion' – the concentration gradient is a function of the combined effect of these two factors. The hydrodynamic model within CONNIE3 calculates the transport effect separately, so this should not be included in the characterisation of decay rate.

- Vertical integration is not currently part of the preferred options in the CONNIE3. Where data need to be integrated across multiple dispersion depths this must be undertaken as a post-processing analysis. IMAS have done this for the outputs modelling dispersal patterns associated with proposed salmon farming operations in Storm Bay. It would be worth considering establishing a standardised protocol for post-processing.

Appendix G: References

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