

LITERATURE REVIEW OF BIOECONOMIC IMPACTS OF POLLUTANTS AFFECTING MARINE PARK ENVIRONMENTS

**Report Prepared by the Centre for Agricultural & Regional Economics
Pty Ltd for the NSW Office of Environment and Heritage**

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Executive Summary

Pollution originating from diffuse and point sources may impact negatively on marine environments, including marine parks. This can have undesirable economic consequences for use and non-use values, both within and outside the reserved area.

Bioeconomic modelling, where the biophysical and economic components of the marine system are explicitly represented and linked is one method for assessing the ecological and economic outcomes of pollution. Models can be used to determine the magnitude of economic impacts, provide insights into cost-effective pollution abatement options, help to measure the effectiveness of marine reserves as a buffer against pollution shocks, and examine optimal levels of pollution abatement.

This report provides a literature review of studies that may help inform future bioeconomic modelling of pollution in NSW marine parks. Due to the limited number of Australian studies directly related to this topic (and most of those are focussed on the Great Barrier Reef), a range of other relevant studies are discussed. Many of these are from overseas, or examine different but related issues (especially fisheries management and marine parks). These studies include modelling parts of marine systems (e.g. species population dynamics in the face of external shocks) which could be adapted to bioeconomic modelling of pollution.

Some key factors emerging from the literature review include:

- Most Australian bioeconomic modelling studies of marine pollution have been performed in the Great Barrier Reef (GBR) region, and investigate the impact of diffuse-source pollution from agricultural and urban run-off on the reef. While this has some relevance to NSW marine parks, reef-based economic activity in NSW is limited, and the marine environment lacks the GBR lagoon which tends to capture and concentrate river plumes. Moreover, NSW rainfall events are usually less intense and mixing of the run-off more rapid in heavy seas. Hence NSW marine parks are unlikely to be subject to the steadily rising levels of nutrients that are found in the GBR lagoon (Peter Davies, personal communication 2011).
- Some models are true bioeconomic models as the biological and economic components are directly linked, and feedback can occur between the various model elements. Other models consist of separate biological and economic components, where the output from the biological model becomes an input to the economic model, but no direct feedback occurs;
- Other models estimate the magnitude of pollution and attach an economic impact to the pollution event without explicitly modelling the ecological system (for example using survey data to elicit tourism demand changes as water quality declines);
- The decision about where to set the system boundary in the modelling emerges in the literature. Often, factors which appear to be outside the system can have

important feedback effects within the system and decisions need to be made regarding resources, model complexity and 'where to draw the line';

- Population dynamics modelling may need to include the concept of a minimal viable population size. The risk of population collapse can be important;
- Synergies between different pollutants mean that the impact on the ecology can be non-linear. None of the studies reviewed appeared to cater for this;
- Adding stochastic elements to the system model can be uncertain - for example is the perceived randomness in population levels truly stochastic or an unexplained process?;
- Modes of pollutant uptake by organisms may need to be considered, e.g. direct uptake versus uptake through the foodchain;
- Dose-response relationships are important, and are unlikely to be linear, with key threshold levels likely to exist;
- Assumptions regarding impacts on species whose value is derived from direct consumption and their prices may need to cater for potential supply-price effects;
- The entry and exit of economic agents into the system (especially marine parks) can alter the ecological and economic dynamics of a pollution incident;
- Marine parks and their interactions with non-reserved areas can be modelled using metapopulation analysis techniques, where different environmental 'patches' are treated as heterogeneous in nature;
- The complexity of ecological interactions between species may require that more than the dynamics of a single species be included. For example, predator-prey interactions might be important drivers of the dynamics;
- A large amount of work has been performed on modelling fisheries population dynamics, and this could be used to inform pollution modelling work. Evaluation in most of these studies is focussed on the commercial fish catch and commercial fishing is limited in marine parks. Some studies do however make valuations of recreational fishing and non-consumptive visitation activities which are highly relevant to NSW marine parks. ;
- The importance of species dispersal mechanisms, particularly in the work conducted on the effectiveness of marine reserves, should be reviewed in relation to pollution impacts;
- Pollutant dilution and breakdown is important.

Acknowledgements

CARE wishes to acknowledge the assistance provided by staff at the NSW Office of Environment and Heritage (John Fountain, Peter Davies, Jocelyn Dela-Cruz and Nick Conner), Chu Long and Tom Kompas (Australian National University), Gustaaf Hallegraeff (University of Tasmania) and Peter Roebeling (University of Santiago). The time taken by these people to provide references and information is greatly appreciated.

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1 The Basis and Scope of the Study

1.1 Introduction

The origin of this report lies in the legislation that establishes Marine Parks and the Marine Parks Authority in NSW. Under the Marine Parks Act 1997, the Authority has a number of functions which are relevant to the issue of pollutants and their potential impact on marine park environments including:

- To manage and control activities that may affect marine biological diversity, marine habitats and marine ecological processes in marine parks;
- To provide for and regulate ecologically sustainable use (including commercial and recreational fishing) in marine parks;
- To encourage public appreciation, understanding and enjoyment of marine parks and, where consistent with the other functions of the Authority, public recreation in marine parks,
- To encourage and permit, when appropriate, scientific research into the ecology of marine systems.

An independent review of marine park science conducted in 2009 suggested that more emphasis should be placed in the future on integrating socio-economic studies with biophysical studies to improve the effectiveness of the management of marine parks. This literature review study represents an initial step in addressing that recommendation.

1.2 Study Objectives

- Carry out a literature search of on-line economic and environmental publications databases accessible via the Office of Environment and Heritage to identify material relating to the economic impacts of pollutants which affect biodiversity, human health and amenity values relevant to NSW marine parks;
- Critically review this material in terms of its relevance to NSW marine park environments;
- Present the results of the above search and review as draft, and draft final reports.

1.3 Study Tasks

Three main tasks were indicated:

Task 1 - Literature search of on-line economic and environmental publications databases accessible via the Office of Environment and Heritage library. The focus is on locating studies (journal articles, books, research reports, other publications) relating to the bioeconomic impact of pollutants which affect

biodiversity, human health and amenity values associated with **Australian coastal marine environments** including marine parks. The focus is on studies relating to:

- Australian marine/coastal environments;
- Marine park environments;
- The east coast of Australia;
- NSW coastal environments in particular.

The pollutants to be considered include:

- Sediment, nutrient and pathogen runoff from agriculture;
- Point and diffuse discharges of trade and domestic effluent;
- Waste from fishing activity;
- Waste from vessels.

Potential impact of pollutants to be considered includes:

- Changes in water quality leading to damage to marine environments and species;
- Water contamination leading to impacts on biodiversity and water user health;
- Deoxygenation of environments leading to loss of flora and fauna, species diversity and productivity;
- Dead or dying flora and fauna leading to loss of amenity and recreational values.

Task 2 - Critically review material in terms of relevance to NSW marine parks. This task involves assessing studies in terms of their relevance to NSW marine park environments, with regard to the bioeconomic issues discussed, the analytical approach used and the results of the analysis.

In particular, commentary is sought on the ease with which the analysis and modelling approaches could be applied to economic studies in NSW marine parks.

Task 3 - Provide reports on Tasks 1 and 2 above.

2 Task 1 – On-line Literature Search of Economic and Environmental Publications

Relevant references found during the literature search are provided in a separate Excel spreadsheet provided with this report, and are also summarised in Appendix 1 of this report.

In addition to general internet searches for references to ‘marine pollution’, the following on-line databases accessed through the Office of Environment and Heritage intranet were searched:

- EconLit;
- Environment Complete;
- Cambridge Scientific Abstracts;
- Web of Science;
- Current Contents Connect;
- GreenFILE;

- International Coral Reef Symposium Proceedings;
- Sciencedirect;
- National Ocean Economics Program database on environmental and recreational values/valuation;
- Office of Environment and Heritage full-text journal list.

3 General Theory Relating to Economic Impacts of Marine Pollution

In this section, relevant studies located during the on-line literature search (listed above in Section 2) are critically reviewed in terms of their potential applicability to marine parks in NSW. In Appendix 1 these studies have been segregated according to the pollutant investigated, and a summary of each study and its relevance to pollution in NSW marine parks is provided in a tabular format.

The following sections provide some more detail on the mechanics of the modelling approaches used, and outline the factors that would need to be considered were these approaches to be applied to pollution impacts in NSW marine parks.

Several references provided a generic overview of pollution effects and their economic treatment. These would be useful for informing any future bioeconomic modelling of pollution in NSW marine parks.

Ofiara and Seneca (2001) have produced a handbook for the assessment of economic losses from marine pollution, which covers economic theory with a focus on marine pollution in relatively simple terms compared to most of the studies discussed below. The publication also covers a range of other issues including pollution legislation (in the US), the impacts of reduced water quality in marine environments including biological effects on various species and humans, and some worked examples of estimating economic losses.

The handbook provides quite a detailed discussion of the correct measures to use when developing models to assess the impacts of marine pollution and this is pertinent to bioeconomic modelling. In the context of marine pollution which can impact on both consumers and producers, economic welfare analysis at the aggregate market level (i.e. the sum of aggregate consumer and producer surplus) is the correct measure of the change in economic value. This is assessed as the difference between the economic welfare in the economy without pollution and the economic welfare in the presence of pollution, and is equivalent to calculating the net economic value of the change in pollution status (Ofiara and Seneca 2001). Several issues of particular note include:

- The distinction between the negative 'economic impacts' of marine pollution which can include items such as lost sales, output and employment, and the reduction in 'economic value', which is the accurate measure of the change in economic welfare measured via reductions in consumer and producer surplus. Economic value is the correct measure for use in cost-benefit analysis. While the calculation of other

'economic impacts' can provide additional information on locational or employment effects (e.g. through the use of input-output analysis), they are not strictly measures of the change in net welfare (net economic value) – pp. 114;

- The intricacies of calculating consumer and producer surplus are discussed including the potential for double-counting transfers of surplus between producers and consumers – pp.147-148;
- The use of the 'with and without' rule to more accurately ensure the correct economic welfare losses from marine pollution are being estimated – pp. 145;
- Starting on pp.171 is a useful table listing the possible impacts of marine pollution, the economic activities impacted, the possible economic effects, and the likely losses in economic value (or welfare). The loss in economic value is partitioned into potential consumer and producer surplus losses, and provides a valuable check on the economic values that could be included in bioeconomic models and how they might be measured;
- Chapter 9 (pp. 273-324) provides a critique of a number of case studies on the economic damage resulting from marine pollution. The chapter provides important insights into some potential 'economic traps' that can be encountered when calculating welfare losses.

Some of this material is repeated in Ofiara (2001), however this reference also provides a useful summary of techniques used to measure net economic value including:

- **Contingent valuation**¹, where direct measures of economic value are assessed from surveys. These values represent *ex ante* (before) measures of welfare based on anticipated willingness-to-pay for hypothetical market goods. Care in questionnaire design is important for eliciting accurate estimates. The author discusses how various biases can be introduced into the process and how this can be avoided.
- **The travel cost approach**, where indirect valuation is derived from observed behaviour, hence is *ex post* (based on activity that has already occurred). The dollar value of a trip cost is taken to be a measure of the satisfaction derived from an additional trip/visit. Again, some shortcomings and variations of the technique are discussed.
- **Hedonic travel cost approach** modifies the travel cost approach to account for variations in site quality to generate the marginal costs associated with site characteristics. The approach involves regressing travel costs on site characteristics/environmental quality attributes. The author reports that problems with the approach have limited its application.

¹ Contingent valuation is a stated preference technique based upon a survey of potential consumers. More recently, choice modelling has been developed as a means of refining the technique.

- **Property valuation techniques**, where property valuations are used to evaluate changes in environmental quality, thus valuing the satisfaction derived from characteristics related to property location. This satisfaction can be modified by pollution incidents. Fairly sophisticated econometric techniques are involved.
- **Valuation of morbidity and mortality health effects**, where marine pollution has negative health effects. This includes valuing lost earnings from loss of participation in the labour force (the authors discuss several serious shortcomings with this method), or an assessment of what an individual is willing to pay to avoid illness or death (via the contingent valuation method, and again the authors discuss some of the issues impacting on accuracy of estimates).

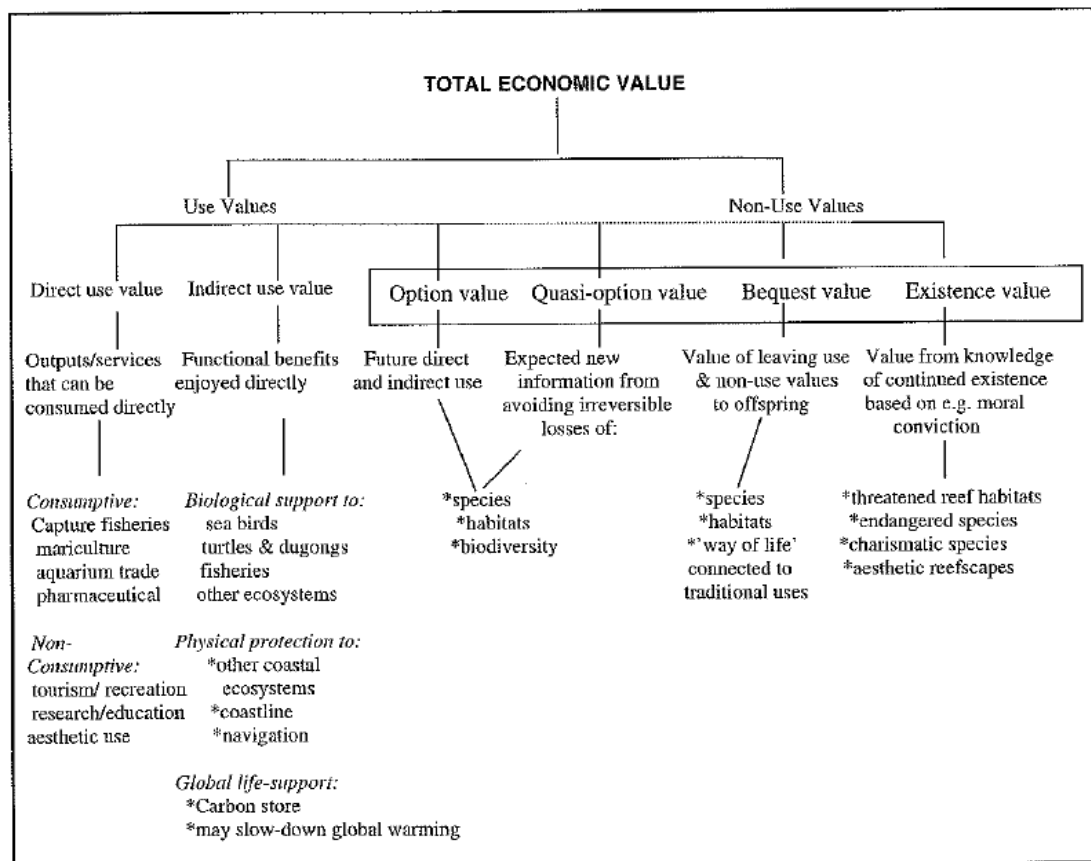
The calculation of producer surplus loss from marine pollution can be difficult as private firms may not wish to divulge cost and revenue information, and the magnitude of loss of business activity is not always clear. Ofiara (2001) proposes a method to calculate the loss by comparing the sales/rents and costs of similar businesses for both the 'with' and 'without' pollution periods, and calculating the difference between the two periods.

Subade (2007) explores valuation issues with respect to potential loss of marine biodiversity (which could be the result of marine pollution), and in particular explores the concept of Total Economic Value (TEV) which includes both the use and non-use values of environmental resources such as biodiversity. Biodiversity values have been classified as:

- Biodiversity production values, with a supply oriented approach to valuation where biodiversity is part of an economic production function (e.g. contributes to the value of a fishery);
- Biodiversity utility values, measured within an economic utility function which is a demand oriented value such as consumer surplus. Contingent valuation is often used to estimate non-use utility values;
- Biodiversity rent capture values, which are more about identifying a particular profit share captured by a location or interest group, rather than forming a part of the TEV estimate.

A useful overview of the various components of TEV for a coral reef is reproduced below, showing the partitioning between use and non-use values, direct and indirect use values, and non-use values such as existence and bequest values. Examples of each type of value are also included, and while coral reefs are not a major feature in NSW marine parks, the various categories of values provide a useful checklist for items impacted by pollution which could be included in bioeconomic models. Some care needs to be taken however as the elements listed in Figure 3-1 represent both stock and flows and there is also a risk of double-counting some values.

Figure 3-1 Total Economic Value: attributes of economic values for coral reefs



Source: Subade (2007), p.139

Some economic values are then reported (Tables 1 and 2, pp. 140) for a reef marine park. Based upon the definitions of producer and consumer surplus outlined above, it appears that some of these values may be an overestimate as they appear to state the gross values of the fish catch or park entrance fees, rather than the net values (e.g. for producer surplus, production costs need to be deducted from gross revenues). Similarly, the willingness-to-pay (WTP) estimates in Table 2 would appear to be over-estimates as they have been applied to the entire population, when more recent studies of benefit extension suggest this is not the case. Estimates should only be applied to the proportion of the population which equates to the proportion of survey respondents. Non-respondents are deemed to have zero WTP (e.g. see Morrison *et al* 2002).

Tisdell *et al* (1992) describe methods for measuring the economic losses from marine pollution as it relates to tourism impacts. The theory discussed relates to net losses in producer and consumer surplus from pollution, and the impact of elasticity of supply and demand on the magnitude of those losses. Potential losses of government taxation revenues as a result of reduced foreign visitation are also explained, though it should be acknowledged that taxes are usually regarded as transfer payments, and do not form part of economic surplus measures.

From an empirical viewpoint, the estimation of relevant supply and demand curves can be difficult and it is proposed that researchers may be compelled to use professional judgement and trade off analytical rigour for empirical feasibility.

One complication is that uniform pollution across all tourism sites means demand shifts for tourism may not be evident if alternative locations are not available, although there could still be a loss of utility which is not reflected in actual demand levels.

Tisdell raises the concept of an optimal level of pollution control, the logic being that there is rarely an economic case for eliminating pollution entirely. The economic social optimum will be achieved when the marginal net benefits received from polluting activities (e.g. fertiliser applications in farming) equal the marginal external costs of pollution imposed (e.g. detrimental impacts on marine species and hence tourism). The economic case for stronger pollution controls is dictated to some extent by the availability of substitutes in the tourism marketplace. If there are few substitutes, the pollution marginal cost curve will be steeper (i.e. a small amount of pollution imposes a relatively greater cost on the tourism industry), and hence the case for government intervention will be stronger. This is a relevant factor when considering the economic impacts of pollution in NSW marine parks. The availability of substitute locations for commercial and recreational activities, and the extent of the pollution problem will have a direct bearing on the shape of the pollution marginal cost curve and hence the importance of the impacts.

Further complexity is added to the calculation of tourism impacts when it is considered that some individuals may be willing to trade-off environmental quality for lower-priced tourism activities, and that different types of pollutants can impact on different characteristics of tourism utility (e.g. seafood contamination versus surfing opportunities).

In section 4, a more detailed discussion of references specifically relating to bioeconomic models is provided, and the implications of these studies for assessing pollution impacts in NSW marine parks are drawn.

4 Bioeconomic models

The review of the literature revealed a number of models described as 'bioeconomic models' which have either been applied directly to marine pollution issues, or have been used to investigate other aquatic/marine issues (e.g. fishery management and marine park creation) and which provide a potential framework around which bioeconomic models for pollution could be developed. These include:

1. Deterministic bioeconomic models which estimate the impacts of pollution on commercial fisheries, and include the important biological elements of pollution loading and impacted species population dynamics (e.g. Collins *et al* 1998).
2. Quite complex stochastic bioeconomic models not related to pollution, but which examine in detail key elements of ecosystem function (e.g. species population dynamics) and their response to external policy decisions which impact on economic

agents operating within the system (e.g. Greenville and MacAulay 2006, 2007). These models contain a number of characteristics which would be applicable to modelling marine pollution impacts in parks.

3. Deterministic mathematical optimal control models (e.g. Roebling *et al* 2007), which examine the benefits of marine environments, the cost of pollution and link this to the benefits derived from the polluting activity (in this case terrestrial land use). This type of model does not explicitly model ecosystem function (though it could be included).
4. Models which incorporate a spatial element via the use of GIS technology into classic economic Computable General Equilibrium (CGE) models (Smajgl *et al* 2009). While this type of model examines pollution impacts, it does not include the important non-market values of marine environments.
5. A multi-criteria approach, where no detailed modelling is conducted, but expert opinion is used to score the likely ecological and economic impacts of pollution (Greiner *et al* 2005).

The key features of these modelling approaches and their applicability to developing bioeconomic models for NSW marine parks are outlined in the following section. Some of the important ecological and economic factors which might need to be considered if developing similar models for NSW marine parks are also discussed.

4.1 Bioeconomic models which specifically examine pollution impacts

One of the most comprehensive models found during the literature search was that constructed by Grigalunas *et al* (1988) which examined the impacts of oil and diesel spills in marine environments in US waters. While from a geographical perspective, these environments are far removed from NSW ecosystems, the approach provides an insight into the immense level of detail which can be built into bioeconomic models to assess pollution impacts.

The model (known as the Natural Resource Damage Assessment Model for Coastal and Marine Environments) contains a large amount of detail on both the nature of the pollutant and the natural resource systems impacted. In summary, the structure of the model includes:

1. **A physical fates submodel** with a chemical database of 14 parameters and 469 oil and chemical substances. Key features of this submodel include:
 - Physical, chemical and toxicological data;
 - Simulation of the spreading, mixing and degradation of the pollutant in various layers of the water column and the bottom sediments;

- Parameters relating to tides, wind speed/direction, water column depth, air temperature, distance to shorelines and boundaries, to estimate pollutant transport and fates;
- This submodel outputs the concentration of the pollutant by location over time, and this is passed to the biological effects submodel where environmental damage is simulated.

2. **A biological effects submodel** with the following features:

- A database on the abundance of various finfish, shellfish, marine mammals and birds across 10 US provinces/ecosystem types;
- Abundance is segregated by season, bottom type, marine vs estuarine and tidal vs subtidal environments, leading to 364 different ecosystem-season categories;
- Above a threshold level of pollutant, acute biological injury is calculated including direct losses of adult and juvenile birds, fish and shellfish and for fish larvae;
- Another simple model estimates indirect losses as a result of food web impacts;
- Both short-term (e.g. loss of adult fish) and long-term (e.g. reduced recruitment from loss of larvae) are included;
- Sublethal impacts were ignored due to lack of data;
- The long-term effects of pollution are handled via a routine which simulates the dynamics of different species populations by age classes. This routine, which simulates changes in the population from one time step to the next, includes parameters for natural mortality, fishing mortality (as a function of biomass, catchability and fishing effort), and biomass (as a function of length and weight).
- Injury to birds and mammals is calculated using the same cohort type model used for fish species.
- The output of this submodel is the reduction in biomass for various species as a result of pollution impact by season and location, which becomes input for the economic submodel.

3. **The economic effects submodel** includes:

- Calculation of the change in value for economic entities utilising the resources, based around changes in profitability. This essentially relies on reduced revenues from reduced harvest as a result of biomass loss for those industries (e.g. fishing) which harvest species (i.e. loss of producer surplus).

It is assumed supply impacts are too small to have any price effects. Note that no loss of consumer surplus for reduced consumption of fish is included, the (unstated) assumption being that consumers are able to source fish from elsewhere, hence suffer no such loss.

- Recreational fishery losses are calculated in a similar manner to commercial fisheries, based upon estimates of the loss of consumer surplus per unit loss of recreational catch;
- Fish resources damaged by a pollution incident are allocated between commercial and recreational uses;
- Injury to birds are deemed to result in both consumptive and non-consumptive losses (e.g. viewing, photography) and damages are calculated using marginal values of additional harvests (consumptive) or marginal changes in the value of visitor days (non-consumptive). Losses due to reduced beach visitation are based upon consumer surplus per visit.
- Discounting is applied to damages to estimate the net present value of the economic damages over the time period until the system completely recovers.

The modelling approach described in the Grigalunas *et al* (1988) study relies upon a large amount of actual biophysical and economic data (see Table 6-1 for details) to populate the equations in the model. This data is used in the Ricker model which simulates the dynamics of the fish population by age classes.

Economic valuation for harvested species (fish, birds) was achieved by valuing the changes in fish harvest levels as a result of the pollution incident. Changes to species biomass (and hence the catch level – both commercial and recreational) are the primary variables estimated in the model to which economic value is attributed. Economic values are based upon market prices for commercial species and the marginal value per fish or bird for recreational species.

In a similar manner to consumptive losses, economic values associated with non-harvested species (birds, seals) are based upon changes in population and consequent changes in visitation, with marginal values per visitor day being applied.

Some important features of the Grigalunas *et al* (1988) approach that are worthy of consideration in the NSW marine parks context are:

- The complexity and data-intensive nature of the models would require considerable ecological modelling expertise and resources. While the economic components of the model are relatively straightforward (though also data intensive due to the wide range of species included), the biological systems are complex, particularly with the inclusion of a food web component (details on how this operates are sparse in the study);

- Population dynamics of all species appear to be based around fisheries models. The applicability of this approach warrants further consideration;
- It is assumed that the system always recovers to its initial equilibrium as the pollution incidents considered are 'minor'. This may not always be the case;
- The number of species/locations/season types to be considered in the NSW situation is likely to be substantially less than for the entire US;

Population levels for fish and birds are the primary parameter which changes as a result of pollution, and from which economic impacts are estimated. These would mostly be relevant to marine parks where recreational harvesting is allowed, or where visitation levels might change as species populations change, therefore the applicability of this model would require the capacity to estimate changes in recreational demand in NSW marine parks. Commercial fishing is restricted in NSW marine parks, so changes in commercial harvest levels are less relevant.

Another early piece of work which involved the development of a bioeconomic model to assess the impacts of an unspecified pollutant on commercial fishery profits was conducted by Collins *et al* (1998). While it is acknowledged that commercial fishing activities are limited in NSW marine parks, this study provides insights into some of the essential modelling features that are required to capture the impacts of pollution on biological systems. Several key elements are modelled including:

- Loading of the pollutant into the environment, which is determined by the initial concentration, the supply rate, and the dilution of the contaminant through flushing and sedimentation. This model represented a 'semi-enclosed' (lake) system where it was assumed the water was 'changed' during the course of a year via inflows and outflows. For a marine system, depending on location, flushing and sedimentation rates may depend on other factors such as tidal movements.
- Loading of the pollutant in the target species (fish stocks) was based upon the concentration of pollutant in the environment, and parameters which determine uptake and elimination by the impacted species.
- Pollutant concentrations in the impacted species are transformed into changes to mortality and fecundity by describing a marginal impact of the pollutant on these factors. A threshold level of pollutant load, below which no impact results is also defined.
- Population dynamic equations describe the number of fish by age class at a given time step as a function of natural mortality and harvesting (fishing) activity. Fishing related mortality is a function of catchability of the species, fishing effort, fish biomass and the vulnerability of the species to fishing. Recruitment of new stock is included in the population dynamic on the basis of the size of the spawning stock and the number of recruits per spawning stock.

- Pollution-induced mortality is added to the population equation, as is the effect of pollution in reducing fecundity through a reduction in the number of eggs produced.
- The behaviour of the economic agents in this system (the fishing fleet) is described in terms of fishing effort, measured as entry and exit of vessels into/out of the fishery system on the basis of profit in relation to total costs. Profit greater than zero will result in a proportion of vessels entering the fishery in the next time step, while negative profits will result in vessels exiting the fishery.
- Total economic damages in the system are calculated as the net present value (NPV) of net profits over the period since the pollution event occurred. Again, the focus here is on producer surplus, impacts on consumers of fish appear to be assumed as zero.

Both the ecological and economic components of the system modelled by Collins *et al* (1998) are represented in a much simplified manner compared to reality. For example, population dynamics are based on a limited number of determinants (e.g. mortality, fecundity, growth) which in themselves are all complicated processes driven by a host of interacting factors. This type of simplification is typical of bioeconomic models, where the focus is on capturing key system drivers and their response to policy or other shocks. Consequently, many parameters are represented as simple fractions or rates of change, rather than becoming sub-models themselves within the main model. For example underlying mortality is set at a constant rate for various age classes of fish, rather than also being modelled as a result of factors such as water temperature, predation etc.

The data utilised in the model appears to be rather general in nature, rather than being based upon a detailed analysis of any particular dataset, and so somewhat arbitrary parameters are used to populate the model equations. Changes to the commercial harvest level of fish is the parameter upon which the economic of pollution are valued.

The need to 'draw a line around the system boundary' and make simplifying assumptions about model parameters is a common feature of all bioeconomic modelling, though the extent of this process clearly varies (e.g. the Grigalunas *et al* 1988 model includes far more detail in terms of biological submodels, species, locations, seasons and pollutant types).

The Collins *et al* (1998) study highlighted the important result that economic damage from pollution is not just related to impacts on the natural resource, but also the response of economic agents (in this case fishing businesses) within the system. Where vessels rapidly exited the system after the pollution event, the recovery of fish populations was more rapid, a consequence of reduced fishing pressure. In this case, market forces operate so as to mitigate both environmental and economic damage. However, this effect may not be observed for other economic agents (e.g. tourists seeking visual amenity or recreational values), where their withdrawal from the polluted resource has no impact on the rate of recovery of the resource.

Several other potential shortcomings of the Collins *et al* (1998) approach which are ignored in the model, but may inform future modelling efforts include:

- No minimum stock size from below which no population recovery is possible was included;
- There are no stochastic (random) variables in the model;
- Some pollution incidents involve several contaminants which have a non-linear synergistic impact;
- Pollution impacts on mortality and fecundity may be non-linear;
- Uptake of the pollutant by organisms may be via foodchain effects, as well as direct uptake from the environment. This would require modelling of the pollutant in the food sources of the species of economic interest;
- Supply impacts within the system may have an effect on prices if the system of interest is a large component of total supply. Again, this raises the need to consider system boundaries and potential important feedback effects that might occur from outside what is considered to be the logical boundary. Economic damage may depend on conditions outside the immediate ecological system and those inside it;
- Entry and exit of economic agents into and out of the system may not be symmetrical due to issues including asset fixity and restrictive licensing requirements. This may increase the costs from pollution in terms of forgone production and is likely to be pertinent to operations in many marine parks.

The importance of marine species dispersal factors as a determinant of the effectiveness of marine reserves is discussed in the following sections (especially section 4.2), however Massey *et al* (2006) specifically address the issue of dispersal behaviour as a response to water quality (pollution) levels. They point out that a 'reduced form approach' to modelling the impacts of water quality on angler welfare, which uses cross-sectional data to link trip frequencies, catch rates and water quality will not measure important dynamic effects of the short and long run impacts of water quality change. These dynamic factors largely refer to the effect of fish migrations on responses to changes in water quality.

Massey *et al* (2006) have developed a dynamic bioeconomic model of a recreational flounder fishery, and the most important element in this work which may inform bioeconomic modelling of pollution in NSW marine parks are the sections relating to fish abundance and water quality. These components of the model have the following key features;

- The functional relationship between water quality, summer flounder survival and abundance and harvest (commercial and recreational levels) is described;
- Different flounder age structures are represented to account for different sources of mortality at different ages;
- Spatial structure is included to account for migration between coastal waters and open ocean. They also define a particular 'study area' of bays and estuaries which is

treated separately to other bays and estuaries and is the focus of the pollution impacts;

- The population model estimates juvenile numbers and survival rates, juvenile dispersal, numbers of spawning adults, adult dispersal and adult harvesting rates from both commercial and recreational anglers;
- Key parameters in determining these population levels include survival rates, population growth rates, fecundity rates, natural mortality rates, catch rates, number of recreational fishing trips, average commercial harvest levels and site fidelity (the genetic pre-disposition of individuals to return to the same bays/estuaries);
- The critical link between population dynamics and pollution is the dissolved oxygen (DO) concentration, which impacts on juvenile flounder survival rates in the bays and estuaries. DO concentrations can reach low levels when high nutrient loads are flushed into coastal areas after storms. A probability of survival at different DO levels function is used, based upon data from laboratory experiments. Actual DO data from monitoring stations within the study area is used to estimate survival over summer period;
- The authors note a weakness in the pollution aspects of the model, namely that survival over the entire summer season under a long run of intervals with low DO levels would be equivalent to the same duration of low DO levels, but more evenly spread out over the season. This is unlikely to be the case;
- Note that the dose-response function for juvenile summer flounder survival and DO concentrations are non-linear, with survival increasing rapidly within a very narrow band of rising DO levels. This has important implications for modelling pollution impacts, because it suggests that the benefits of pollution abatement may diminish rapidly once pollution is reduced below a certain level;
- A key feature of the model is that the time scales for changes in water quality can be as short as 15 minute time-steps, as opposed to the annual average water quality measures used in reduced form models.

The model draws upon actual water quality data from monitoring programs and catch data from angler surveys, so in that respect is populated with 'real world' data, rather than typical average values.

While economic valuation is based upon both commercial catch rates and the demand for recreational fishing trips, it is the recreational fishing component of the model which is of most relevance to the marine park situation. Survey data was used to place a value on recreational fishing trips, as a function of the number of fish caught. Therefore, pollution which reduced fish numbers will impact upon the value of the recreational fishing experience. This is directly relevant to NSW marine parks, where recreational fishing is an important economic activity and reason for visitation to the area.

Massey *et al* (2006) demonstrate that a structural bioeconomic model which explicitly captures population dynamic characteristics will produce very different results to a reduced form model which ignores these intricacies.

In summary, the studies reviewed in section 4.1 illustrate several important considerations to guide future modelling of pollution impacts in NSW marine parks:

- The level of model detail to be included (e.g. number of species, ecosystems and pollutant types) varies significantly and will likely be determined by the resources available to conduct the study, and the availability of data;
- The issue of setting the system boundary, as factors which might initially be seen as being outside the boundary can actually feed back into the system and modify the impacts of the pollution incident;
- Consideration of how the pollutant loads into the environment, how it loads into impacted species, and the effect on the species (e.g. mortality, fecundity) including consideration of whether the impact is linear (unlikely) or not;
- The interaction between economic agents in the system and ecosystem recovery from a pollution incident;
- The importance of capturing species dispersal mechanisms, which can determine the value of marine parks as a buffer against pollution shocks;
- Commercial fish (and bird) harvests were key features of all models and are likely to be of less economic relevance in marine parks. However recreational harvests and visitation for other purposes (e.g. photography) were also examined in some studies, and are highly relevant to NSW marine parks.

4.2 Bioeconomic models of other marine issues

One of the most relevant pieces of work is the development of a biophysical model of NSW marine environments (Savina *et al* 2009). The model was developed as a tool to address issues emerging along the NSW coast, and though the emphasis is on the effects on fishery productivity, the effectiveness of marine reserves is also investigated in the study.

Known as the 'Atlantis' model (a framework which has been developed over the past decade – see Fulton *et al* 2011), the approach builds upon management strategy evaluation (MSE) techniques, and the modelling framework incorporates:

1. **A deterministic ecosystem model** including physical, biogeochemical, and higher trophic level components and processes:

- This component is nutrient based, with water flows determining spatial exchanges between model layers;
 - Water temperature and salinity can be fixed, or allowed to vary dynamically in response to a range of physical factors such as water mixing or rainfall;
 - Seabed physical properties can change as a result of sediment deposition and other factors;
 - Key biological groups in the model (e.g. nutrients, detritus, bacteria, invertebrates, vertebrates) are linked through trophic interactions (e.g. growth, reproduction, predation, migration). Relatively detailed biological information is used to capture these effects (e.g. swimming speed of fish, migration routes).
2. **A deterministic sector model** that emulates the effects of fishing and other human activities on the ecosystem:
- Pollution, commercial and recreational fishing, habitat modification, introductions of exotic species, and climate change can be simulated in the model;
 - Pollution can be either point-source or diffuse, though the biological responses are currently limited to temperature, salinity or nutrient issues;
 - A wide range of fishing methods can be examined;
 - Sophisticated dynamic fishing fleet models can be used to estimate fishing effort on the basis of responses to socio-economic parameters, and effort can respond to factors such as fish stock depletion or marine reserve creation;
 - Changes to habitat through processes such as dredging can be simulated;
 - Exotic species introductions can be simulated;
 - Physical and chemical consequences of climate change can be simulated.
3. **A sampling model** that collects data from the ecosystem and sector models and calculates indicators:
- Extracts output data from the above two models and analyses the data;
 - Analysis is well developed for fisheries data, but not for other environmental outputs.
4. **A management model** that regulates the human activities sector model.
- Results of the sampling model feed into the management model. Management options are then applied with or without adaptive feedback (e.g. restrictions on contaminant inputs, declaration of marine reserves, fishing restrictions).

The model scope extends offshore as far as the upper continental shelf and also caters for a range of ocean depth zones. Broad functional groups for 54 biological groups including plants, bacteria, invertebrates, finfish, sharks, marine mammals and birds are catered for. Some commercial fish species are modelled at the individual species level.

A simulation based framework is used which explicitly caters for uncertainty in the dynamics of the ecosystem or socio-economic system. The impacts of human activities and the implementation of monitoring and management programs are captured in the model.

Atlantis is a 'box model' - all model variables are computed within a finite number of horizontally layered polygonal boxes with horizontal and vertical exchanges between adjoining boxes. It supports arbitrary spatial and temporal scales, though the number of boxes and the model time-step are limited by the available computing capacity. The spatial structure of the model considers habitats, organisms, physical processes such as tidal movements, and human impacts. The time-steps in the model vary depending upon the ecological process being mimicked.

The model is populated using data from a range of sources including NSW Fisheries databases and NSW government river flow databases.

Modelled output of physical, biological and human parameters are provided in time series and with spatial distributions. In the report, outputs investigated under a range of fishing strategies included value of catch, number of over-fished species, number of extinct species, and a biodiversity index. The impact of marine reserve development was also examined.

Interestingly, the marine parks scenarios revealed the sensitivity of the ecosystem to population dynamics effects, such that the positive impact on predator population numbers was offset by a negative effect on the numbers of prey species. This increase in predation actually led to a reduction in biodiversity. However, the same result, but of larger magnitude was also found when fishing was reduced through reserves, but fishing effort outside the reserved areas is not reduced (e.g. through the use of buy-backs). Where fishing effort outside the reserve *was* reduced, the negative impact on lower order predator and prey species was lessened.

The situation where the introduction of reserves and other measures which reduce fishing pressure lead to a *reduction* in prey species and hence overall biodiversity may seem counter-intuitive, given species lower down the food chain (i.e. prey species) typically have higher fecundity and would respond more rapidly to the creation of a favourable environment (reserves) and reduced fishing pressure. However, it appears that in this case, the predator fish groups were already over-fished, and hence reduced fishing pressure allowed their recovery, with a subsequent negative impact on prey species

The modelled results tend to support the intermediate disturbance hypothesis; with very high fishing pressure (redistributing fishing effort from reserved to non-reserved areas) biodiversity falls through direct fishing mortality and with very low fishing pressure (reduction and no redistribution of historical fishing effort), high predation reduces biodiversity.

While some elements of Atlantis are still being developed, the model appears to represent a well-developed starting point for the bioeconomic modelling of marine pollution impacts in NSW marine parks. The effects of pollution on key ecosystems and species could be added (from the report cited, it is not clear to what extent pollution impacts are already developed

within the model). The capacity to measure the effects on some market values (e.g. fish catch value) already exists, however augmentation to include non-market values (e.g. consumer surplus derived from recreational fishing) would need to be added.

To date, the primary focus of economic valuation in the Atlantis model appears to be based on the net economic benefits derived from commercial fisheries.

The Atlantis model has also been used to examine the effect of diffuse-point pollution from land-based nutrient flows (nitrogen) in the Clarence River estuary (Hayes *et al* 2007). The focus of this study was to investigate nitrogen concentrations under different river flow regimes and the impact of phytoplankton, zooplankton and chlorophyll biomass. Again, this represents one potential component of a bioeconomic model which has direct relevance to NSW marine parks.

However, the modelling result suggesting that marine parks reduce biodiversity (Savina *et al* 2009) may be a symptom of the data, modelling assumptions and re-calibration. For instance, the study appears to rely heavily on Fisheries data from 1979 and the area of coastal waters closed to fishing appears to overestimate the actual area of Marine Parks in NSW.² In addition, it is understood that the authors had to modify Gemfish catch rates to produce a satisfactory model calibration. These results are at odds with modelling done in NSW Marine Parks using baited underwater video (e.g. Malcolm *et al* 2007) which show an increase in the number of prey species such as Red Morwong and Snapper. It is unlikely that reduced fishing in (the relatively small-sized) no-take zones in NSW Marine Parks would significantly increase shark populations.

In addition to bioeconomic models specifically focussing on marine pollution effects, Greenville and MacAulay (2006, 2007) have developed bioeconomic models to assess the changes to fishery resource rents (profits) as a result of the establishment of protected areas. While not directly examining pollution issues, this approach is applicable to NSW marine parks in as much as it establishes a method within bioeconomic modelling where protected (i.e. park) and non-protected marine areas can be examined.

Their modelling approach utilised the concept of metapopulation analysis, where different spatial environments contained sub-populations of a single biomass. Because the focus of this study was on protected areas, this allowed specification of sub-populations in protected areas and non-protected (fishing ground) areas.

The authors make the point that ecological interactions within fisheries are complex and modelling a single species may be sub-optimal, so two species (labelled predator and prey species) were modelled. While this may imply a level of complexity beyond what has been examined by previous researchers, the discussion of the Grigalunas *et al* (1988) work outlined above illustrates that in the past, far more complex models have been developed

² While Savina *et al* do not specifically state the size of Marine Park areas closed for fishing in their model runs, the areas closed for fishing in figure 3.3.1 (MP2 and MP4) seem to overstate the actual range of Marine Parks in NSW (see: <http://www.mpa.nsw.gov.au/pdf/NSW-Marine-protected-areas.pdf>).

which capture multiple species and predator-prey interactions via a simplified food web component.

Population dynamics in the Greenville and MacAulay (2006, 2007) work include growth and dispersal functions for predator and prey species, predation effects, and commercial harvest of both predator and prey species as a function of catchability, the level of fishing effort and the biomass present.

The dispersal function is an important parameter in the population dynamics of this model. Its importance lies in the capacity of both prey and predator species to move between 'patches' (i.e. from the protected to the unprotected areas), and this has important implications for the value of establishing protected areas. These different patches are deemed to be heterogeneous in nature.

Economic value is captured using net social value (NSV) expressed as gross revenues (calculated from harvest levels) minus costs, and the model is solved to find the optimal level of biomass in each patch, being the level of biomass which maximises NSV. So the measure of change in economic value is based upon producer surplus (and note, this is the correct calculation as costs are deducted from gross revenues, which does not appear to be the case in some other work as discussed below). Note these economic values are confined to commercial fishery catches, with data in the Greenville and MacAulay (2007) study being drawn from NSW DPI records. No attempt was made to value the recreational or non-consumptive uses of the fishery.

Specification of the predator-prey interaction involves parameters describing the intrinsic growth rates of the species, the carrying capacity of the patch, dispersal, predation for the prey species and fishing harvest.

The model also contains a parameter which estimates the risk of stock collapse (unlike the Grigalunas *et al* 1988 model, where population always returns to equilibrium), such that the risk of collapse declines as the size of the protected area within the fishery is increased. The risk of collapse term is incorporated into the calculation of NSV, such that NSV declines as the risk of stock collapse increases. This ensures the fishery is not overvalued.

A final element of note in the Greenville and MacAulay (2006) approach is the inclusion of a stochastic (random) growth rate, set up as triangular distributions with different parameters for both prey and predator species. Interestingly, these growth rates are deemed to be independent of patch size, which is a questionable assumption if patch size has an effect on competition for food and other resources within the patch. Presumably however, this effect is dealt with by means of the patch carrying capacity parameter.

The modelling process elicited the socially optimal marine protected area size under differing assumptions about growth rate correlations between species and patches, and two alternative dispersal patterns (density-dependent and source-sink). Negative opportunity costs (i.e. gains in NSV) were observed for protected areas of various sizes, though once this size became larger (20-50% of total area), positive opportunity costs (i.e. losses in social value) were observed.

The hypothetical model constructed for the Greenville and MacAulay (2006) study was then populated with data for the Manning Region of NSW (hence the applicability of this work to NSW marine parks), and a range of scenarios examined based around growth rates combined with the creation of protected areas. The general conclusion is that while protected areas could improve both fishing resource rents and reduce harvest variations, reductions in resource rents were mostly observed. Dispersal between patches and protected patch size were the key determinants of the benefit generated. The importance of marine reserves as a source of 'positive spillovers' (e.g. fish dispersal from reserved to fished areas), is also discussed in detail by Grafton *et al* (2004).

The Greenville and MacAulay (2006, 2007) studies raise a number of issues which might be pertinent to the development of pollution assessment models in marine parks:

- They describe a metapopulation approach which captures biomass interactions between protected and non-protected areas. This could be relevant if pollution is restricted to a particular area to capture the potential population recruitment (recovery) benefits of marine parks;
- Their data is directly applicable to NSW marine environments;
- The approach raises the possibility of modifying the growth functions for predator and prey species in response to pollution effects;
- It is noted in the study that only supply side issues (fish populations) were considered. Demand side issues associated with the non-use values of habitat and species protection could also be included;
- The importance of dispersal type in determining economic outcomes may be relevant to pollution events, should the event cause a density-dependent dispersal species to switch to a source-sink dispersal mode to escape pollution. Note that Grafton *et al* (2004) have also emphasised the importance of accurately capturing dispersal in bioeconomic models of marine reserves, and that sink-source type dispersal can have an important bearing on the location of the reserve;
- There may be parallels between fishing harvests and pollution events if the pollution event is limited to a discrete area.

Bioeconomic modelling of marine reserves with an emphasis on the implications for fishery management was also reviewed by Grafton *et al* (2004). This model is based upon a theoretical representation of the system, with hypothetical values for parameters being used, rather than drawing upon observed data from an actual fishery. Again, catch rates and hence returns from a commercial fishery were the focus of economic valuation.

While many of the conclusions reached (e.g. the importance of dispersal mechanisms from reserve areas) are covered elsewhere in this report, several issues stand out which may help inform bioeconomic modelling of pollution impacts:

- Spatial modelling has demonstrated that the location of reserves requires understanding both biological and economic factors, as both will drive the nature of economic activity within the reserved and non-reserved parts of the marine environment.
- Adding stochastic elements (uncertainty) to models can be important for the simulation of negative shocks on species populations (e.g. a pollution shock), and ascertaining the chance of species elimination. The 'safety net' characteristics of reserves may allow greater economic exploitation of marine resources while ensuring long-term sustainability.
- Stochastic modelling to date indicates that uncertainty has implications for the size of reserve required. Kompas *et al* (2010) have further indicated that the size of marine reserve should increase with the size of the negative shock to ensure population persistence. This has implications for marine reserves in NSW as a buffer to pollution events, assuming some forms of pollution can be avoided/controlled in reserved areas.
- An important conclusion is that reserves established for fishery management may need to be designed differently to reserves created for other purposes (e.g. for biodiversity and habitat maintenance). This is because reserves for fishery management must be of a size that allows dispersal from reserved to harvested areas. In contrast, if the purpose of the reserve was to mitigate against the effects of a negative shock such as pollution, reserve design and size characteristics might be different. Bioeconomic modelling of pollution impacts on marine reserves may therefore have to account for multiple anthropogenic factors (e.g. the combined effects of pollution, harvesting and recreational activities) to capture both the combined impacts, and to reach conclusions about the effectiveness and design of reserves as a buffer against pollution.
- Stochastic bioeconomic modelling of reserves suggests that establishing reserves to meet multiple objectives is difficult.

In Kompas *et al* (2010), a more detailed exposition of optimal reserve size in the presence of fish harvesting is provided. While this work focuses on fisheries management, there are important clues in the modelling system for pollution impacts, as sensitivity to negative shocks (e.g. pollution) are factored into the fish population equations for the reserved and non-reserved areas.

This dynamic optimisation model is hypothetical/theoretical in nature, rather than being populated with data from a real-world system. Commercial fishery harvest levels and values are the economic measure used to compare the benefit of marine reserves of different sizes.

Source-sink population dynamics are at the core of the modelling methods, where population growth in reserved and non-reserved areas is expressed as a function of population size, the intrinsic growth rate (a proxy for fecundity presumably), and the total

population carrying capacity. A transfer function which governs migration to and from the reserve is also specified in the population model.

Ecological uncertainty is introduced into the model in two forms:

1. Environmental stochasticity (can be positive or negative) due to temporal variation in habitat represented as a normal distribution; and
2. Random negative shocks as a jump process, but where the sensitivity to the shock differs in the reserved and harvested populations.

The system of equations is solved to maximise the economic value over all possible reserve sizes under the optimal harvest level at each reserve. A similar approach could be applied to the pollution problem; i.e. for pollution shocks of various magnitudes both inside and outside reserved areas, what is the optimum reserve size, given the effects on economic values of both the reserve (e.g. impact on fishing or recreational activities) and the pollution incident.

The Kompas *et al* (2010) simulations show that a reserve can result in fish populations and hence economic value recovering more rapidly following a negative shock (the resilience effect). However, in the absence of such a shock, larger reserves will reduce harvest and economic values. There comes a point (a critical reserve size) where the marginal benefit (the transfer of fish from the reserved to the fished area after a shock) will equal the marginal cost of foregone harvest in the non-reserved area. In terms of informing future bioeconomic impacts of pollution on NSW marine reserves, this result emphasises the importance of assumptions relating:

- The possible differential impact of pollution in reserved and non-reserved areas and the capacity of populations in reserves to 'bounce-back' more rapidly and re-populate non-reserved areas;
- The dispersal potential between reserved and non-reserved areas;
- The impact of establishing reserves on economic activity – unlike the fishery case where the impact on fishing within the reserve is negative, when a wider range of economic values are considered (e.g. tourism as well as fishing), there may be positive (tourism) and negative (fishing) economic trade-offs to be considered with reserve establishment. If pollution shocks outside the reserve are offset by species dispersal from within the reserve, there may be no economic trade-offs (i.e. tourism within the reserved areas is maintained, and fish harvest levels outside the reserved areas bounce back more rapidly);
- The frequency and magnitude of negative shocks will be critical in determining the net economic benefit from establishing reserved areas;
- Modellers may need to consider the differential impacts of pollution in reserved versus non-reserved areas – are there instances where the different nature of these areas leads to different effects? Kompas *et al* (2010) note that reserves may not

provide a hedge against negative shocks if the sensitivity of the population within the reserve is greater than outside the reserve.

Rolling reserves and dynamic switching regimes are also discussed by the authors, where marine reserves can move spatially in response to shocks or population densities, and the size of the reserve may vary. This could be a management option used to deal with unpredictable pollution events (e.g. oil spills), and switching economic activity to a previously reserved area results in a more immediate return to profits.

In summary, the studies reviewed in section 4.2, while not all explicitly modelling pollution, illustrate some factors which may need to be considered when conducting bioeconomic modelling of pollution impacts:

- The 'Atlantis' model represents a well developed biophysical model of NSW marine systems which may provide a logical starting point for bioeconomic modelling of pollution issues. It already includes the capacity to simulate pollution issues, and the economic attributes of commercial fishing fleets;
- Some of the studies explicitly include 'negative shocks' which provide examples of how pollution could be modelled;
- The studies discuss the possibility of those shocks having differential impacts inside and outside reserved areas;
- The frequency and magnitude of shocks is an important determinant of the economic benefits arising from reserve establishment;
- Again, dispersal is critical in determining the effectiveness of reserved areas in providing resilience against negative shocks;
- Modellers may need to consider if the sensitivity of species to pollution differs inside and outside a reserved area.

4.3 Optimal control models of marine pollution

The deterministic optimal control model used by Roebeling *et al* (2007) to assess the impacts of terrestrial pollution on the Great Barrier Reef differs from the true bioeconomic models outlined above in that no attempt is made to model the biophysical aspects of the ecological system in any detail. Rather, the benefits from terrestrial land use (residential and agricultural) and marine environment benefits (use and non-use values) are expressed as a function of the level of marine water pollution, and the equation is solved to elicit the level of marine pollution which maximises combined net benefit (welfare).

Using this approach, it is assumed that terrestrial land uses, while generating certain benefits, also contribute to increasing levels of marine pollution as population expands. Marine benefits are assumed to decrease in a linear fashion as marine water pollution increases.

The theoretical model is then parameterised for the Douglas Shire catchment in Qld by estimating parameter values for terrestrial land use benefits, terrestrial land use water pollution and marine benefits.

A 'classic urban economic model with environmental amenities' was used to estimate terrestrial land use benefits. On the land demand side, this is based around the concept of households maximising their utility (subject to their budget constraint) on the basis of factors such as residential spaces, environmental amenity value and access to non-housing related goods and services. The budget constraint relates to housing rental prices and commuting costs.

On the land supply side, land developer profit maximisation is based upon rental prices net of land development costs, where development costs comprise the opportunity cost of land and housing construction costs.

At equilibrium, where housing demand equals supply, the system of demand and supply equations can be solved to elicit the land rent price at a given location.

In the absence of pollution, the objective function of the model is to find the mix of agricultural and residential land uses for a given catchment population which maximise total terrestrial land use benefits. This model was parameterised for nine different population scenarios in the Douglas shire, and the numerical output subject to regression analysis which allows total terrestrial benefits to be described as a function of catchment population.

Water pollution from nitrogen under different land use and population scenarios was calculated using a separate biophysical model. This is a key point of departure of the Roebeling *et al* (2007) modelling approach from classic bioeconomic models (e.g. Grigalunas *et al* 1988), as the biophysical component of the system (nitrogen pollution) is estimated *externally*, and then incorporated into the welfare maximising problem, by applying a range of potential margin costs to nitrogen water pollution.

The welfare maximising equation therefore assesses the tradeoffs between terrestrial land use benefits and the costs of water pollution to calculate the size of the catchment population which maximises net welfare. Actual marginal pollution costs could not be estimated, so sensitivity analysis was performed across a range of marginal pollution cost levels (expressed in dollars per tonne of nitrogen), to estimate the resulting optimal population size.

Unlike a more integrated bioeconomic modelling approach, the method described by Roebeling *et al* (2007) is more theoretical in nature, and does not involve a direct establishment of the links between pollution, the biological systems being impacted, and the subsequent effect on economic values. This reduces the potential for the researcher to gain an appreciation of the mechanisms and potential feedback effects which operate within

bioeconomic systems, unless they become familiar with the workings of the externally applied biophysical model. Roebeling *et al* (2007) make this point in their conclusions in relation to population growth being an exogenous variable in the model, when in fact it should be endogenous as population influx may decelerate or accelerate as residential development impacts on environmental and urban amenities. For example marine pollution may exert a negative feedback effect on population growth, such that the social costs of pollution encourage pollution abatement over time. This type of dynamic effect is not captured in a model of this nature.

In summary, the study reviewed in section 4.3 does not directly link the ecological system to the economic system:

- The objective of this model is to determine the optimal level of pollution, given that there are tradeoffs between the benefits that flow from polluting activities and costs that arise from pollution;
- The biophysical component of the model calculates pollution levels, but not their direct impacts on species etc. Rather, those pollution levels are converted directly to pollution costs;
- Pollution abatement costs are not considered, and for the model application in the Douglas Shire, the marginal costs of pollution could not be determined, and sensitivity analysis was performed to investigate optimal population size;
- It is assumed the negative impacts of pollution are linear – this is unlikely to be the case as revealed in more detailed bioeconomic models;
- This approach will not capture important feedback effects both within ecological systems and between the economic and ecological systems.

4.4 Combined models of marine pollution

Models falling under this category are bioeconomic models in the sense that they specifically simulate both biophysical and economic systems, however the biophysical and economic models are separate components (closed systems essentially), where output from one model becomes input to the next.

Roebeling *et al* (2009) describe a model of this nature which is used to investigate cost-effective methods of achieving specified water quality targets in the Tully-Murray catchment, which generates outflows to the GBR by altering land-use and land management practices.

The model integrates output from three main components:

1. **Two agricultural production systems models** (APSIM and PASTOR) which simulate sugar cane production and pasture-based beef production. Key features of these models include:
 - APSIM generates estimates of cane production, ground cover, soil water balance, nitrogen uptake and partitioning of leaf and stem. Biophysical factors (e.g. soil depth) are combined with crop management factors (e.g. planting date, fertiliser use, tillage methods) to generate these outputs;
 - PASTOR generates the production of beef, ground cover and nutrient balances based upon a complex interaction between pasture growth and stocking rates. Inputs and outputs for pasture, beef cattle and feed supplementation are calculated based upon both biophysical factors (e.g. soil depth and nitrogen availability) and management factors (e.g. stocking rate, fertiliser use, genetics).
 - These models also output soil loss and dissolved inorganic nitrogen estimates.
2. **A river-nutrient export model** which takes the soil and nitrogen losses from the agricultural models, and estimates location-specific contributions of these land uses to end-of-catchment total suspended solids (TSS) and dissolved inorganic nitrogen (DIN) delivery. The model can be used to estimate the proportion of local water pollution supply that ends up at the river mouth, and hence contributes to marine pollution.
3. **A spatial environmental-economic land-use model** with the following features:
 - Biophysical land characteristics which vary with location and determine agricultural production potential;
 - Climatic and soil conditions vary by location and in combination with land use and management practices determine water pollution supply;
 - Farmers use existing infrastructure to access markets/processing plants and cost and revenue differences between different processing options are considered;
 - A mathematical optimisation model is solved to maximise regional agricultural income based on land-use and yields, production costs, distances to markets, transport costs and processing costs (i.e. the model is maximising producer surplus);
 - End of catchment water pollution delivery from each location is determined by the fraction of local water pollution which reaches the river mouth.

Estimates are made of the changes in area for sugarcane and grazing landuses that are required to meet various reductions in TSS and DIN levels (ranging from a 35-80% reduction in these pollutants). Output data from this analysis can then be used to fit a

quadratic water pollution abatement cost, based around the reduction in regional economic income resulting from different levels of pollution abatement. Note that these abatement costs would appear to correspond to reductions in producer surplus, as the economic measure used is agricultural income net of variable costs according to the income function provided on pp. 1152. It appears that this function actually calculates *net* regional agricultural income.

Results suggest that through changes in management techniques, the sugarcane industry can generate improvements in pollution levels in the order of up to 35% while actually *increasing* net income – a result of these techniques being more profitable but less polluting in nature (e.g. minimum tillage and modifications to fertiliser applications).

However, for the grazing industry, all improvements in water quality come at significant cost, a result of limited management options for water quality improvement.

The modelling approach also provides spatially explicit information on the locations where the most cost-effective reductions in water pollution can be achieved. The authors note that the TSS and DIN pollution abatement functions are estimated separately, when in fact in many cases reducing sediment runoff would also reduce DIN levels. Consequently, the results may underestimate the level of water quality improvement at each level of abatement cost.

The potential for water pollution management actions to reduce several pollutants simultaneously should be considered in any bioeconomic modelling for NSW marine parks. However, the Roebeling *et al* (2009) study provides no information on parameters within marine parks which could be directly valued when making an assessment of pollution impacts. Rather, it demonstrates a technique for calculating pollutant *levels* in marine environments under alternative land uses. Additional steps would then be required to estimate the effects of the pollutants on marine park biophysical features, and subsequent changes to economic values.

The modelling approach is deterministic, so does not account for the fact that while the cost of adopting 'best management practice' is partially irreversible, the benefits of adoption (and hence impacts on pollution runoff) are uncertain.

Incorporating uncertainty into models of this nature was outlined by Herr and Kuhnert (2007), where parameters which contribute to the Revised Universal Soil Loss Equation (RUSLE – used to determine sediment transport into streams and ultimately into marine environments) are set up as probability distributions rather than fixed parameters. The issue of correlation between uncertain variables in conducting stochastic analyses of this nature is discussed.

Smajgl *et al* (2009) have combined a Computable General Equilibrium (CGE) Model with an Agent Based Model (ABM) under an approach described as Integrative Assessment and Modelling (IAM). These integrated models include the system components and the interactions between them, and can be utilised in a decision support process where the modelling is not isolated from the stakeholders.

The argument has been advanced that for Decision Support Systems to be used in natural resource management decisions, an integrated process which involves stakeholders is more likely to result in adoption, and the modelling method should integrate system elements from different foci. Smajgl *et al* (2009) apply this method to the issue of nutrient loads entering the GBR.

A catchment level CGE model has been modified to include key production inputs to irrigated agriculture including water, fertiliser and labour. In addition to economic production functions with input and output variables reacting to market prices, production functions for irrigation water are developed with water inputs (e.g. from rainfall) and water outputs (irrigation use, remaining groundwater).

Response functions for ecosystem services and species are also included in the model. For example, nutrient flows from fertiliser applications are tracked, which impact on other processes such as seagrass production. Seagrass is a food source for other species such as dugong, which has an impact on tourism revenues. The model is solved using the algebraic modelling software GAMs. The Integrated CGE model therefore assesses both market values and non-market aspects of the system.

The approach is further enhanced through combination with an ABM which adds a spatial dimension using GIS visualisations of land and water use decisions. The decision making process within the ABM includes both market and non-market values and model output includes land use decisions made by agricultural agents. Essentially, the decision is based upon both a non-market utility function in combination with a costs and revenues based payoff function within the ABM. The system is dynamic in nature in as much as the agents can modify their production input mix in response to changing agricultural market conditions. In combination with the GIS capability, this allows land use, economic and environmental indicators to be displayed in a spatial context.

The key feature of this approach is that it extends CGE modelling beyond a system which is entirely dependent upon market driven dynamics, to also include non-market values and their physical dynamics (i.e. nutrient loads in water, downstream impacts of water quality on biological function, species, and the subsequent economic effects), and does so in a spatial context.

This approach would entail a number of advantages if applied to pollution impacts in NSW marine parks, in particular:

- Both economic and biophysical factors are examined;
- Market and non-market values can be included in the analysis, and importantly the feedback effects between these two types of values is captured;
- There is a high level of stakeholder involvement, rather than the modelling process being conducted in isolation (the 'blackbox' problem);
- Impacts are displayed spatially, so geographic areas of differential impact can be identified.

However, application of this process to NSW marine parks would require advanced skills in CGE modelling, including the ability to modify such models to include biophysical inputs/outputs as opposed to the standard economic models. GIS capability is also required.

Some of the models discussed elsewhere in this report (Roebeling *et al* 2007, Kragt *et al* 2009) have been linked in a prototype Bayesian Belief Network (BBN) by Thomas *et al* (2009) to investigate the impact of DIN runoff from the sugarcane industry on the vulnerability of GBR coral to climate change effects. It has been established that reduced water quality increases the likelihood of coral bleaching as water temperature rises.

The procedure, applied to the Tully-Murray catchment in Qld, involves the linking of:

- A deterministic spatially explicit model of the agricultural economy (see Roebeling *et al* 2007 and 2009) which includes landuse, management practices, contributions of DIN to river mouth output and agricultural income;
- A model for coral bleaching which integrates the DIN information with a river water dilution model and projection of sea surface temperature change;
- A reef tourism model which provides an integrated bioeconomic risk assessment for reef condition, agriculture and tourism at the catchment level. This model uses expert judgement to assess the relationship between coral bleaching and tourism, and estimates the effects on tourism demand and income. The authors acknowledge that the quantitative understanding of the relationship between coral bleaching and tourism is poor.

The modular approach of linking five separate models allows information on three different sectors (agriculture, reef condition and tourism) to be linked, without compromising the complexity of the scientific mechanisms being investigated. This may be an important consideration for any future bioeconomic modelling of pollution in NSW marine parks. Attempting to develop a fully integrated bioeconomic model may require system simplifications that compromise accuracy. The linking of extant and more fully developed models for different system components (e.g. agricultural landuse, pollution runoff, marine ecosystem and economic models) may produce a more robust and accurate framework. However, the issue of correlations between variables in the different model components may need to be considered.

In summary, the studies reviewed in section 4.4 link biophysical, economic and spatial models whereby output from one model becomes input to another.

- This approach, if applied to pollution in NSW marine parks could entail the use of existing models;
- Again, unlike an integrated bioeconomic model, the issue of feedback effects is likely to be excluded;

- The approach has been used to examine the cost-effectiveness of pollution abatement;

- The issue of correlations between stochastic model variables is discussed;
- One of the studies used GIS analysis to add a spatial component to the modelling, which provided information on the most cost-effective locations to apply pollution management options.

4.5 Multi-criteria models of marine pollution

A multi-criteria approach elicits information from experts on the suitability of various management actions. Greiner *et al* (2005) describe such an approach for the analysis of diffuse-point pollution in the GBR. A set of criteria and attributes relating to that criteria are described and scored, to make an assessment of the impact of pollution on various parts of the GBR river basin.

The following criteria and attributes were described:

1. Ecological impacts of diffuse-source pollution, defined by attributes:
 - Increase in riverine suspended solid load since 1850; dissolved inorganic nitrogen load; mean river flow; pesticide concentrations; basin connectivity; basin beef cattle numbers, basin aquatic ecosystem condition, total reef circumference in basin area of influence, total area of seagrass in basin area of influence, development pressure.
2. Social impact of pollution prevention, defined by attributes:
 - Agricultural production value; income from agriculture; agricultural productivity; NRM infrastructure; community capacity to change.
3. Economic impacts of pollution, defined by attributes:
 - Value of marine tourism activity in river impact area, value of commercial fishing in river impact area, land-based pollutant attributes.
4. Development pressures (no individual attributes developed).

Once the initial attribute scoring was completed, a second workshop was held for experts to reach consensus on the overall criteria scores across all basins, by ranking the criteria as low, medium, medium-high and high impact. Individual summed and weighted criteria for each river basin provide an overall attribute score for each basin, and this is also provided as an impact summary assessment.

With regard to the applicability of this approach to bioeconomic modelling in NSW marine parks, the approach is different to the studies described in other sections of this report, which apply a rigorous objective quantitative analysis. In contrast, the multi-criteria approach relies upon a subjective scoring and weighting of economic and biophysical criteria derived by 'experts'.

The approach may be a useful precursor to developing a more formal quantitative bioeconomic model for marine park pollution issues in NSW. It could provide key information on the pollutants of highest likely impact, the regions most likely to incur negative effects, and the scope for effective management. The process could help identify priority areas where more detailed bioeconomic models should be developed.

The study approach does not generate any parameters to which economic valuations can be applied.

In summary, the study reviewed in section 4.5 uses expert opinion via a multi-criteria scoring and weighting system to assess which catchments were likely to be most impacted by pollution.

- No formal bioeconomic modelling is used in this approach;
- This method may be an important precursor in determining the issues to be addressed, and the locations to be targeted in a subsequent more formal quantitative bioeconomic model.

5 Other modelling work related to marine pollution which could inform bioeconomic modelling

The literature search revealed additional references which could be used in the development of bioeconomic models of pollution in NSW marine parks.

Where nitrogen pollution and eutrophication of coastal lagoons and estuaries are the focus, Sanderson and Coade (2010) have developed an empirical model for NSW ecosystems, and made a comparison of modelled versus observed results for seagrass coverage. The modelling involves a range of parameters including nitrogen loads and concentrations, chlorophyll concentration, radiation and coverage of benthic macrophytes. Estimates are generated for the potential for changes in eutrophication, light extinction and ecological state as a result of nitrogen export into lagoons. This work could assist in informing the biophysical component of and future bioeconomic modelling.

Consumer welfare estimates for diving and snorkelling activities on the GBR under two different (hypothetical) levels of reef condition were investigated by Kragt *et al* (2009). A contingent behaviour (CB) survey was used to elicit changes in people's behaviour

contingent on a change in reef quality as a result of nutrient and sediment runoff. A statistical model of reef trip demand was formulated, where the number of planned trips was a function of price paid per trip, perception of reef quality, visitor origin, activity undertaken (diving or snorkelling), gender, education, income and reef quality. Changes in reef quality were deemed to result in reductions of fish abundance (by 80%), coral cover (by 30%) and coral diversity (by 70%).

As expected, visitation rates were negatively correlated with increased price and declining reef quality, positively correlated with proximity to the GBR, positively correlated with diving as opposed to snorkelling, but the correlation with income was insignificant.

Based upon the estimated decline in visitation rate from the survey (an 80% decline), and equations to estimate consumer surplus and change in consumer surplus which are functions of the number of visits, trip price, reef quality and a vector of independent regressors (see pp.218-19), the authors calculate the change in welfare as a result of a reduction in reef quality.

The estimated consumer surplus for a diving or snorkelling trip is A\$184.84. The authors extrapolate these results for the Port Douglas area to estimate the total decline in trip numbers and annual consumer surplus for the entire GBR marine park. Based on trip numbers and median trip prices, loss of income to the diving and snorkelling industry is also calculated. A number of cautionary issues relating to extrapolation of the results to other regions and marine recreational activities are discussed, as is the additional work that would be required to estimate the full consumer surplus associated with reef visitation (i.e. in addition to that derived from snorkelling and diving).

The figures and approach used by Kragt *et al* (2009) could be used to provide data for bioeconomic models of pollution impacts in NSW marine parks, particularly diving activities which occur in the parks.

In terms of options for managing marine pollution, Sarker *et al* (2008) have suggested that for diffuse-source pollution (sediment and nutrient run-off from agricultural land), the impacts on downstream water quality should be regarded as a common-pool resource (CPR) problem. A blend of market-based and non-market based instruments, combined with CPR logic whereby downstream beneficiaries of improved water quality 'compensate' upstream landowners for re-establishing riparian buffers is discussed. This is seen as a more effective management option than regulation. The information contained in this study might be used to inform pollution abatement management options developed within a bioeconomic modelling framework.

Lane and Harisson (2000) have examined the effects of oil contaminants on the survival of GBR coral larvae and report that oil treated with dispersant is far more toxic than the oil itself.

The extent of freshwater plumes and potential pollutant concentrations entering the GBR has been reviewed by Devlin *et al* (2000) in an attempt to identify sediment and nutrient

pollution ‘hotspots’. This study provides information on nutrient transport regimes which may help inform bioeconomic modelling.

A final point on sediment run-off; it has been noted that sediment deposition in NSW marine environments may actually have a beneficial effect on fish populations by increasing nutrients in the system (Peter Davies, personal communication 2011).

6 Data Requirements

Access to data to populate and parameterise bioeconomic models may represent a challenge. Table 6-1 provides an overview of the data and data sources from the literature review studies, and provides some clues on the data requirements for developing bioeconomic models of pollution in NSW marine park systems. Note however detailed information on data and sources is relatively sparse in most of these papers, and tracking down detailed sources is likely to require working back through the vast number of references cited in each study.

It should also be noted that many studies utilise hypothetical rather than actual data for many parameters in their models, as the objective is to develop the modelling framework and test its sensitivity to key assumptions, rather than generate results for a real-life situation (e.g. see Collins *et al* 1998, Greenville and MacAulay 2006).

Table 6-1. Summary of Data Utilised in Literature Review Studies

Reference	Data used	Data Source
Grigalunas <i>et al</i> (1988)	Physical, chemical and toxicological data for 469 oil and chemical substances including density, solubility, vapour pressure, degradation rates in sea water and in sediments, adsorbed/dissolved partition coefficient (Koc), toxicological information for various species	Unspecified
	Coastal and marine environmental parameters including tidal currents, wind speed and direction, water column depths, air temperature, distance to shorelines, boundaries	Set by the model user, source unspecified
	Abundance of finfish, shellfish, marine mammals and birds by 10 provinces/ecosystem types	Unspecified
	Impact of pollutant on species	From standard

	<p>Fish prices</p> <p>Average weights of recreational fish caught</p>	<p>laboratory tests</p> <p>Real prices at dock</p> <p>National Marine Fisheries Service</p>
Sanderson and Coade (2010)	<p>Catchment flows into lagoons</p> <p>Long-term annual rainfall</p> <p>Chlorophyll-a levels</p>	<p>River gauging data from NSW Government database</p> <p>Bureau of Meteorology</p> <p>Direct measurements in lagoons</p>
Massey <i>et al</i> (2006)	<p>Juvenile fish survival as a function of dissolved oxygen</p> <p>Population model parameters</p> <p>Water quality data, fish catch data from angler surveys</p> <p>Catch and recreational demand</p>	<p>US EPA laboratory experiments</p> <p>Government reports, internet databases, peer-reviewed literature</p> <p>Maryland Dept Natural Resources</p> <p>National Marine Fisheries Service survey</p>
Kragt <i>et al</i> (2009)	<p>Change in GBR trip demand due to changes in reef quality, price paid per trip</p>	<p>Contingent behaviour survey</p>
Greiner <i>et al</i> (2005)	<p>Ecological impact of diffuse-point pollution, social impact of pollution prevention, economic impact of pollution (qualitative not quantitative data)</p> <p>Riverine suspended solid load, nitrogen loads, river flows</p> <p>Pesticide concentrations</p>	<p>Expert opinion</p> <p>From published studies in GBR region</p> <p>Based on cane industry application rates</p>
Roebeling <i>et al</i> (2009)	<p>Sugar cane production data including water balance, nitrogen uptake and</p>	<p>Uses APSIM model</p>

	groundcover Beef grazing production data including nitrogen uptake and groundcover Downstream pollution delivery	data PASTOR model data Uses SedNet/ANNEX model data
Roebeling <i>et al</i> (2007)	Downstream pollution delivery	Uses SedNet/ANNEX model data
Greenville and MacAulay (2007)	Fish prices, catch value, data and effort Weather impacts on fish biomass	NSW DPI Monthly rainfall records
Savina <i>et al</i> (2009)	Water exchanges between ocean and bays Freshwater inputs from rivers Fish catch rates	NSW DNR website NSW DIPNR PNEENA database NSW Fisheries databases

7 Model Applications

Table 7-1 provides a summary of the modelling applications from the studies found in the literature review.

Table 7-1. Summary of Modelling Applications

Reference	Application	Parameters for Economic Valuation
Grigalunas <i>et al</i> (1988)	Measurement of economic damage from oil spills in the US	Fish and bird population levels (both for consumptive uses and visitation levels associated with population levels)
Sanderson and Coade (2010)	Development of empirical relationships which describe the potential for eutrophication in NSW	None

	lagoons	
Massey <i>et al</i> (2006)	Impact of water quality changes on the value of a recreational flounder fishery in the US	Fish populations for commercial and recreational use
Collins <i>et al</i> (1998)	Impact of pollution on catch rates and profitability in a hypothetical fishery	Fish populations for commercial use
Kragt <i>et al</i> (2009)	Economic impact on recreational reef trip demand on the GBR from run-off induced reef degradation	Reef visitation levels
Greiner <i>et al</i> (2005)	Sensitivity of GBR catchments to the effects of diffuse-source pollution as a means of prioritising management actions	None
Roebeling <i>et al</i> (2009)	Estimating the cost of diffuse-source pollution abatement actions in a GBR catchment	None
Roebeling <i>et al</i> (2007)	Estimating the welfare maximising population size in a GBR catchment with respect to downstream water pollution costs	None
Greenville and MacAulay (2006)	Assessment of the changes in net social value in a hypothetical fishery as a function of marine reserve size	Fish populations for commercial use
Greenville and MacAulay (2007)	Extension of the hypothetical model to commercial fisheries in NSW to estimate the impact of marine reserves of fishery profitability	Fish populations for commercial use
Herr and Kuhnert (2007)	Development of statistical methods to assess uncertainty in GBR sediment transportation models	None
Smajgl <i>et al</i> (2009)	Development of a model for integrated policy impact assessment in the GBR region	Ecosystem service and species important for tourism
Thomas <i>et al</i> (2009)	Linking models to assess the socio-economic tradeoffs (agriculture versus tourism) associated with	Level or coral bleaching and impact on tourism

	GBR catchment management	
Savina <i>et al</i> (2009)	Development of a tool to help address issues emerging along the NSW coast, particularly related to the ecological impacts of fisheries and the potential role of specific harvest strategies or conservation strategies	Fish populations for commercial use

8 Conclusion

This study has revealed that there is an extensive literature, dating back to the 1970's which apply bioeconomic modelling techniques to the issue of marine pollution and the economic consequences of establishing marine reserves. The later studies have largely concentrated on the benefits to commercial and recreational fisheries from reserve establishment, with little direct emphasis on pollution issues.

However, some studies have explicitly examined the issue of reserves as a buffer against 'negative shocks'. This work could help inform future bioeconomic modelling of pollution in the context of marine reserves. However, the studies outlined above concentrate on the buffer effect, and none of the studies found in the literature review specifically investigate the negative impact of pollution *on* marine reserves.

This literature review reveals that future work on pollution impacts in marine reserves is likely to lead researchers into the area of population dynamics modelling, as species dispersal mechanisms, spillover effects and predator-prey interactions emerge as important determinants of reserve benefits. Given that commercial fishing is restricted within NSW marine parks, the population dynamics of other non-harvested or recreational fish species are likely to assume greater importance.

In terms of the economic valuation of pollution effects, this area is well covered in the literature with a large range of market and non-market based valuation techniques and examples provided. This is particularly useful given that many benefits derived from marine parks are tourism-related, and benefits are based upon visitation rates or non-consumptive existence values. Valuation techniques in this area have been advanced in recent years with the development of Choice Modelling methods.

Appendix 1. Summary of Key Bioeconomic Modelling References Reviewed in the Study

References related to nitrogen/fertiliser pollution in marine environments

Source	Region	Impact	Modelling/analytical approach	Results	Applicability/Application to NSW marine parks
Roebeling <i>et al</i> (2007)	Great Barrier Reef (GBR), Douglas Shire	Nitrogen pollution leading to algal growth and reduced growth/reproduction in coral	Deterministic optimal control (mathematical programming) approach using GAMS (General Algebraic Modelling Systems) software to solve the linear model. Objective is to find the population size that maximises welfare, under different marginal costs of nitrogen pollution	Ignoring pollution costs results in a welfare maximising population for the shire ten times its present level. That population size declines as the downstream costs of pollution are factored in, suggesting that if costs are high (\$5000/t), the optimal; population may only slightly larger than its current level	The result seems fairly obvious given the linear nature of the model, but the interesting finding is the relative optimal size of populations under various cost assumptions. Applicability is moderate due to the lack of coral based tourism in NSW parks. Application of the method would require expertise in mathematical programming and associated software.
Smajgl <i>et al</i> (2009)	GBR	Fertiliser runoff leading to reductions in water quality, potentially leading to reduced seagrass quality, reduced sealife and reduced tourism	Combining a Computable General Equilibrium (CGE) model which has been modified to include hydrological and ecological functions with an Agent Based Model (ABM) which uses a GIS platform to examine spatial issues. Referred to as Integrated Assessment and	Provides a theoretical presentation of modelling techniques can be combined to capture multi-disciplinary system descriptions (i.e. economic modelling, ecosystem modelling, spatial modelling). Broadens standard economic CGE models to include non-market values and physical dynamics, adding a spatial dimension to	Applicability is moderate, with fertiliser runoff from agricultural lands being of some relevance. Application to NSW marine parks would require extensive experience with both CGE models and spatial modelling software (GIS). The CGE models would have to be modified from their standard

			Modelling (IAM)	simulation results.	market value format to include non-market values for environmental goods, and the biophysical interactions that occur (for example irrigation water and rainfall being inputs to downstream flows), fertiliser inputs being an input to water quality.
Roebeling <i>et al</i> (2009)	GBR, Tully-Murray catchment	Impact of suspended sediment and dissolved inorganic nitrogen on water quality. Focus is on most cost-effective way to meet water quality targets.	Environmental-economic modelling approach combining an agricultural production systems simulation model and a catchment water quality model into a spatial environmental-economic land use model	Water quality improvements in terms of reductions in total suspended solids and dissolved inorganic nitrogen can be achieved from changed management practices in the sugarcane industry at no cost, or even at negative cost (where new management techniques are more profitable). However large improvements in water quality will come at a cost. For the gazing industry with less management options, all reductions in pollution incur costs.	Provides an example of how biophysical (agricultural production systems, river nutrient load models) can be integrated with an economic land use model to assess the cost-effectiveness of pollution abatement.
Thomas <i>et al</i> (2009)	GBR, Tully-Murray catchment	Impact of dissolved inorganic nitrogen on water quality and subsequent vulnerability of coral reef to bleaching under climate change induced	Describes a prototype Bayesian Belief Network (BBN), in which rivers link agricultural, GBR and local tourism components.	This holistic view of the system examines tradeoffs for specific reef condition targets, and if these tradeoffs result in a net benefit to the entire reef community.	

		temperature changes.			
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References related to diffuse source pollution in marine environments

Source	Region	Impact	Modelling/analytical approach	Results	Applicability/Application to NSW marine parks
Greiner <i>et al</i> (2005)	GBR	Damage from nitrogen, phosphorous, sediment and pesticide residues on seagrasses and coral and subsequent negative impacts on commercial fishing and tourism	Multi-criteria approach, which typically integrates criteria scores into a single value. In this case, the approach was modified to compare river basins and their contribution to pollution discharge, rather than to compare alternative actions. The criteria (ecological impact of pollution, social impact of pollution prevention and economic impacts of pollution) were scored and weighted. Relies on expert input (via workshops) to elicit scores, weights and interpret net results.	Scoring of individual river basins led to an expert rating (low, medium, medium high, high) of the likely level of impact against each of the criteria, and this provided insights into both the urgency needed to curb diffuse-point pollution, and the type of management mechanisms which should be adopted to achieve pollution reduction. The approach identifies the magnitude of the hazard, the focus area for management and information about the human dimension of the issue (i.e. capacity to respond/change activities).	<p>Applicability is moderate, with fertiliser runoff from agricultural lands being of some relevance.</p> <p>The approach is quite different to studies which apply a rigorous objective quantitative analysis, in that it relies on a subjective scoring and weighting on economic and biophysical criteria derived by 'experts'. This approach may be a useful precursor to developing a more formal quantitative bioeconomic model for marine park pollution issues in NSW. It could provide information on the regions and pollutants of highest likely impact, and the scope for effective management. This process could help identify priority areas where more detailed bioeconomic models should be developed.</p>
Sarker <i>et al</i> (2008)	South East Qld – Moreton Bay	Impact of sediment and nutrient loads on water quality and	An approach in which water quality is considered a common-pooled resource	CPR logic could be used to manage rural diffuse sources of water pollution, by facilitating cooperation	Applicability to the mechanics of bioeconomic modelling in NSW marine parks is minimal, however

		habitat values	(CPR) good. The pollution management agenda could be modified to consider the CPR nature of water quality, which is particularly applicable to diffuse- (as opposed to point-) source pollution.	between landholders, existing NRM and water bodies, and the downstream beneficiaries of improved water quality. Beneficiaries would pay landholders to implement management techniques (largely riparian re-vegetation) to reduced sediment and nutrient loads in rivers. Without cooperation at several levels, the ecosystem market is unlikely to form.	the study provides an insight into possible management techniques, and alludes to factors to be accounted for when estimating the costs of pollution abatement. These costs could be included in bioeconomic modelling.
Massey <i>et al</i> (2006)	US Atlantic Coast	Impact on recreational fishing	Structural bioeconomic model of a flounder fishery, with survival rates impacted by dissolved oxygen levels	Improvements in dissolved oxygen levels can impact positively on juvenile survival rates, adult fish populations and recreational catch rates. Appropriately accounting for the spatial and temporal dynamics of species responses to changes environmental conditions will lead to more accurate analysis of economic outcomes.	The critical element of this reference is the detailed modelling treatment of a pollution impact (nutrient runoff modifying dissolved oxygen levels) on species population dynamics (flounder). Species migration and the pollutant dose-response relationship are shown to be key drivers of the biological and economic outcomes. These lessons are directly applicable to bioeconomic modelling of pollution in NSW marine parks.

References related to non-specified pollution in marine environments

Source	Region	Impact	Modelling/analytical approach	Results	Applicability/Application to NSW marine parks
Collins <i>et al</i> (1998)	Hypothetical	Loss of commercial fishing catch in commercial fishery	Deterministic bioeconomic model of commercial fishery-pollution interactions, including equations to explain the pollution loading in the environment (accounting for dilution, flushing and sedimentation of the contaminant), concentration of the contaminant in fish stocks, impacts of the contaminant on fish mortality and fecundity, fish population by age class accounting for the impacts of fishing and pollution, fishing effort behaviour as a function of current profitability and the present net value of fishing rents (harvest revenues less total costs).	Fishing effort is expected to respond endogenously to pollution-induced changes in fishery productivity, meaning market forces may mitigate both environmental impacts and economic damage (i.e. pollution leads to reduced fish populations, hence reduced fishing effort. This allows the population to recover more rapidly, and for fishing resources to be deployed elsewhere). Economic damage to the fishing resource may be as dependent on the capacity to shift fishing resources to other areas as it is to the eco-toxicology of the pollution event.	<p>Could be used as the basis of a bioeconomic model for NSW parks where the pollutant impacts on the population dynamics of an economically important species (e.g. recreational or commercial fish species, tourist attraction species such as dolphins/whales).</p> <p>This model was for a closed system with no in/out migration of species.</p> <p>No allowance made for minimal viable population.</p> <p>Variability absent in the model, but could be incorporated into the recruitment equation.</p> <p>Pollutant uptake by species may direct, but also via the food chain (the later excluded in this model).</p> <p>Raises some important issues about system boundaries and responses of economic agents:</p> <p>Response of economic agents (i.e. capacity to shift resources)</p>

					determines economic damage; Factors outside the system (e.g. availability of alternative fishing grounds or tourism attractions) may impact this response; economic damage may be via edibility issues, not fish numbers; assumption of constant fish prices may be violated if the species/region in question is a major supply source; asset fixity or licensing arrangements may impede exit/entry.
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Non-pollution related references which may be applicable to bioeconomic modelling of pollution

Source	Region	Impact	Modelling/analytical approach	Results	Applicability/Application to NSW marine parks
Greenville and MacAulay (2006)	Hypothetical	Nil – focus is on impacts on fisheries of establishing marine protected areas	<p>Stochastic bio-economic model of a fishery, including predator-prey dynamics.</p> <p>Modelling just a single species may exclude important results.</p> <p>Uses metapopulation analysis to describe sub-populations of a single biomass.</p> <p>Fishery harvest equation similar to Collins <i>et al</i> (1998) – Harvest = catchability coefficient x effort x biomass, but excludes the Collins relative vulnerability to fishing parameter.</p> <p>Not a closed system like Collins so migration is modelled.</p> <p>Price not affected by catch rate?</p> <p>Examined both density dependent and sink-source</p>	<p>Establishment of protected areas can improve fishery rent and lower harvest variation.</p> <p>For marine protected areas to yield a positive outcome they must reduce the risk of stock collapse occurring.</p> <p>In a policy sense, if protected areas can be established in patches with independent dynamics, where stocks flow to and from the fishing ground, they are likely to maximise the benefits created.</p>	<p>Only supply side issues (i.e. fish populations) were considered, but demand side issues (non-use values associated with habitat protection and species) could be included. Perhaps the approach could be adapted to examine demand side issues in relation to pollution control costs?</p> <p>Growth functions for predator and prey species could be modified to include pollution impacts.</p> <p>A metapopulation approach can be useful to examine marine protected areas. Will capture biomass interactions (e.g. migration) between protected and non-protected areas. Might be relevant if pollution issue is restricted to one or the other area to capture the population recruitment benefits of marine parks to other areas.</p> <p>Metapopulation approach must consider if dispersal is density dependant or sink-source. Could</p>

			<p>dispersal drivers.</p> <p>Has included the risk of stock collapse in the model (Collins noted this was absent from their model).</p> <p>Model is stochastic via randomness in growth rates, which influences harvest and effort as fishers respond to biomass. However growth rates are independent of patch size, when it could be expected that patch size would drive growth rates through competition for resources? Study explored different correlations between growth rates in patches and species to deal with this.</p>		<p>pollution cause a density dependant flow to switch to sink-source (i.e. as individuals move away from the pollution)?</p> <p>Need to consider the impact of different populations on each other (e.g. predators and prey). Can be done through growth rates and examining correlations.</p> <p>Could some pollution events be similar to a fishing harvest (i.e. reduce stock levels in a particular patch), if the effects of the pollution event were limited to a discrete area?</p>
Greenville and MacAulay (2007)	Manning Bioregion NSW	Nil – focus is on impacts on fisheries of establishing marine protected areas	Same model as above for Greenville and MacAulay (2007). However, this model has been populated with data for the Manning Bioregion of NSW and solved examining different scenarios (homogenous biomass growth across patches, creation of protected areas with no fishing with heterogeneous biomass growth, optimising	Although benefits from the creation of protected areas in terms of improved resource rent (fishing profits) and reduced harvest variation are possible, generally, protected areas creation resulted in a decreased in resource rents. The value of protected areas was influenced by several key factors including dispersal type and level (low dispersal resulted in less benefit), the size of the protected patch (there was a limited	While the bioeconomic model did not specifically examine pollution impacts (its focus was the creation of marine protected areas), many characteristics of the model could be relevant to a pollution focussed model. Moreover, the geographic location has high relevance to marine parks in NSW.

			<p>biomass then establishing a protected area). Different dispersal types (density-dependent versus sink-source) were also investigated.</p>	<p>patch size which improved net social benefits), and the use of other management control in the fishery to compliment protected areas.</p> <p>The results also suggested that the protection of high quality areas limited the scope for improving resource rents.</p>	<p>significant amount of detail within the ecological system to cater for factors such as species interactions, dispersal etc.</p> <p>The model also included a 'weather effect' variable which impacts on species biomass. A variable of this type could be used to simulate pollution impacts.</p> <p>Dispersal of biomass to escape pollution events could also be an important determinant of impacts and this model provides a framework to model those effects.</p> <p>The issue of protected areas (parks) and their management providing a hedge against negative shocks (e.g. pollution events) has some parallels with the fishery issues examined in the model.</p>
Grafton <i>et al</i> 2004	General, but includes discussion of Australia	Nil – focus is on bioeconomic modelling of marine reserves as a fisheries management tool, though there is some reference to modelling system 'shocks' (pollution	An overview of the literature pertaining to marine reserves, bioeconomic modelling of reserves and effective fishery management.	Potential benefits of reserves highly dependant on their design (size, number, need to consider species dispersal patterns). Detailed discussion of the spillover effects of reserves, and the factors which influence the size of those benefits. Spatial modelling indicates the location of reserves required both biological and economic	Covers important features of population dynamics modelling in the presence of marine reserves which may inform population dynamics in pollution related modelling.

		might be regarded as a shock).		understanding.	
Kompas <i>et al</i> (2010)	Hypothetical	Nil – focus is on bioeconomic modelling of marine reserves as a fisheries management tool, though there is a strong focus on modelling ‘shocks’ (pollution might be regarded as a shock).	Stochastic bioeconomic model of reserves and a fishery.	Marine reserves can generate economic payoffs, by providing population resilience in the face of external shocks.	Covers important features of population dynamics modelling in the presence of marine reserves which may inform population dynamics in pollution related modelling. In particular, demonstrates how system shocks can be modelled – this could be adapted to pollution shocks.

References related to the principles of measuring economic damage from pollution

Source	Region	Impact	Modelling/analytical approach	Results	Applicability/Application to NSW marine parks
Ofiara and Seneca (2001)	Focus is on the USA	A range of pollutants	Most of the discussion is on methods for estimating economic value (changes in economic welfare) from marine pollution. The text concentrates on the correct methods for calculating consumers and producer surplus, and draws the important distinction between changes in economic value (welfare) and 'economic impacts'. There is also considerable detail on the valuation of non-marketed goods.	Several case studies are provided in Chapter 9 which provide a critique of various bioeconomic studies on marine pollution. There is also a very useful table describing the likely impacts of different marine pollution events and their likely impacts in terms of consumer and producer surplus, and how those values might be estimated.	While the geographic applicability is low, the broad range of pollutants and their effects is highly relevant and the discussion of economic valuation techniques would be most instructive for bioeconomic modelling in NSW marine parks.
Tisdell <i>et al</i> (1992)	Philippines and GBR	Focus is on tourism impacts, from a range of pollutants or reef damage from mining	Theoretical discussion of the economic impacts in terms of shifts in supply and demand of/for tourism services as a result of pollution	Lack of information on the characteristics of marine environments that are important to tourists. Measuring impacts of pollution using consumer and producer surplus requires large amounts of information which is a constraint. Might be better to search for rules of thumb, approximations, qualitative assessments, short-cut	Suggests that traditional economic modelling methods using C & P surplus are too data intensive. Qualitative modelling techniques (e.g. multi-criteria analysis as used by Greiner <i>et al</i> ?) may be more appropriate.

				techniques that can be used to rationally approximate economic consequences of marine pollution.	
Kragt <i>et al</i> (2009)	GBR – Port Douglas region	Estimating reduction in visitation and consumer surplus from snorkelling and diving as a result of pollution induced reef degradation.	A contingent behaviour survey and subsequent statistical analysis of the significance is used to construct a predictive equation of reef trip demand. Information on demand under two different reef quality scenarios is then combined with the survey estimates to calculate changes in consumer surplus.	A significant (up to 80%) decline in reef trip numbers is predicted, for the degradation scenario described. The consumer surplus per trip is estimated at A\$184.84, or a reduction of A\$39 million per year for the region.	Provides a technique for estimating the impacts of marine pollution on tourism activities and the calculation of lost consumer surplus. Could be used in NSW marine park bioeconomic models.

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