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Taxonomic Framework for Valuation of Ecosystem Thresholds

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Table of Contents

List of Tables

List of Figures

Executive Summary

Marine ecosystems provide the basis for a range of industries, including tourism, fisheries and aquaculture. A number of discontinuities exist in ecological regimes: notably in the activity-environmental pressure relationship; the pressure-ambient state relationship; and the ambient state-valuation relationship. This paper draws together evidence on these discontinuities and presents a theoretical framework in which such discontinuities can be integrated and the corresponding damage functions valued and included in policy analysis. Notably, the potential for the application of different market and non-market based techniques for the valuation of threshold effects is examined. Dynamic and stochastic elements are considered within the valuation framework, to take account of non-linearities in general and particular phenomena such as hysteresis within ecosystems and the uncertainty that exists in the precise definition of thresholds

1. Introduction

The importance of marine ecosystems to the economy of coastal zones is obvious. Tourism, fisheries and aquaculture are significant contributors in terms of income to the local economy of most coastal areas. In addition, recreational and amenity benefits arise from properly functioning ecosystems.

The services provided by marine ecosystems have been reviewed in a number of previous articles (eg Scatasta et al, 2003). Often linear relationships have been assumed between ecosystem functioning, nutrient loading and valuation of the ecosystem functions. In recent years there has been growing evidence of the existence of thresholds and points of no return in the scientific literature on ecosystems. The linkage between physical impacts and socio-economic effects have been made and work is starting on bringing the literatures together (Walker and Meyers, 2004). These findings have gradually been integrated into the economics literature (eg Muradian, 2001) – but a consistent framework that could bring together the costs of threshold effects is missing. In this paper we develop such a framework based around the valuation of impacts using economic analysis.

This paper is structured as follows. First, a classification of the types of discontinuities that may exist in marine ecosystems is developed – along with a unifying framework for assessing the impacts in terms of standard cost-benefit analysis. Evidence of these discontinuities is presented using a taxonomy based on a review of the scientific and economic literatures. The framework presented in the first section is developed to consider dynamic and stochastic elements as well as the particular issues relating to hysteresis. A case study of the impacts of a particular threshold effect – that of nutrient loading and consequential algal bloom – is the developed, and techniques to value such “threshold effects” are discussed.

2. Taxonomy of nonlinearities in the analysis of coastal ecosystems

2.1. Overview

From a theoretical perspective thresholds create impacts that require special treatment when valuing externalities. Put simply, if a particular activity creates an environmental pressure such that it changes the ecological regime, there will be a discontinuity in the valuation function (Arrow *et al*, 1995). The figures below shows how these effects arise when there is a discontinuity:

i. In the pressure-ambient state relationship.
ii. In the activity-environmental pressure relationship
iii. In the ambient state-valuation relationship[1]

2.2. Pressure-Environmental state relationship

In Figure 2.1 the relationship between activity and pressure has no thresholds, nor does that between the ambient environmental measure and the marginal damage valuation. But with one discontinuity in the pressure state relationship the external effect of an increase in activity on marginal damages is relatively low up to X_0 and then jumps by an amount Δ, and then reverts back to almost zero after activity level X_1. Examples of this kind of discontinuity are found in the studies on shallow lakes (e.g. Maeler, Xepapadeas and de Zeew, 2000).

2.3. Pressure-Environmental state relationship

In Figure 2.2 there is a discontinuity in the ‘activity-pressure’ relationship. This causes the marginal valuation to remain at zero to the point X_0, where there is a ‘jump’ in the function. After that point the valuation continues as shown. An example of this is given in the case of a marine ecosystem where population loading as a consequence of increased tourist numbers leads to exceedance of the maximum loading of sewage treatment plants, leading to the release of increasing levels of nutrients and faecal coliforms into the marine system. A more realistic version of Figure 2.2 has nutrient emissions rising incrementally according to treatment efficiency (% of person equivalents), but then rising more sharply or equalling p.e. loadings as treatment thresholds are exceeded. Another example may be that of oil spills, where accidents may be represented by a zero emissions level up to a certain level of activity where e.g. congestion makes a collision likely.

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[1] With three possibilities there are in fact 7 combinations of discontinuities to consider. Discontinuous functions and valuation functions are shown in bold

Figure 2.1 Valuation in the presence of discontinuities in the pressure-state relationship

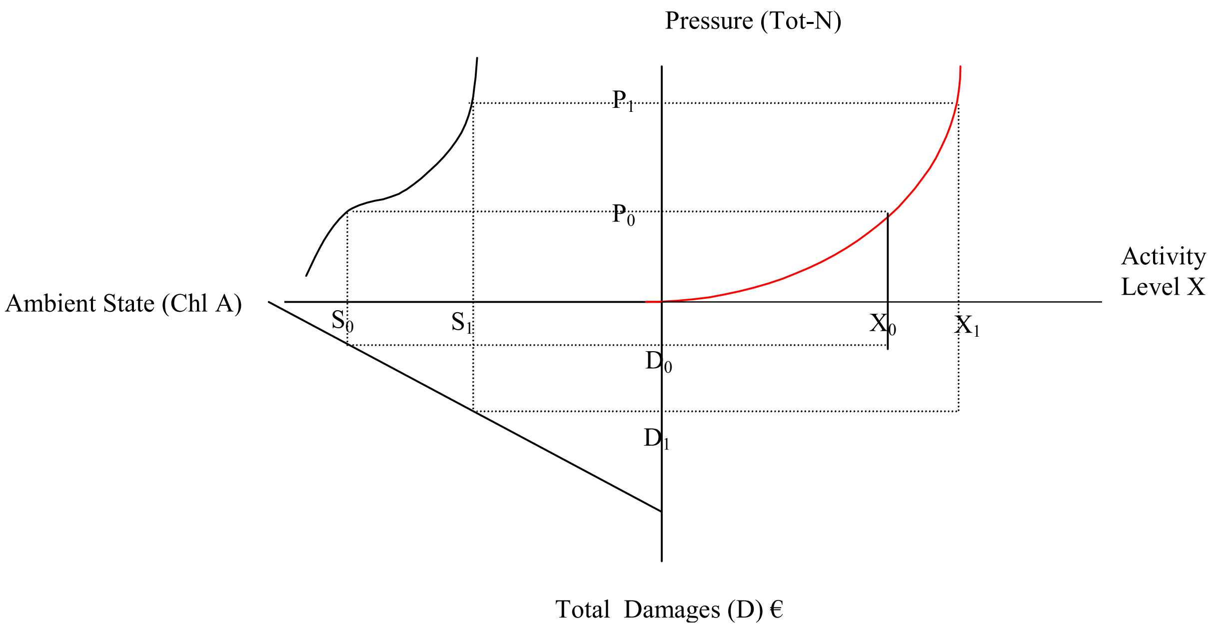
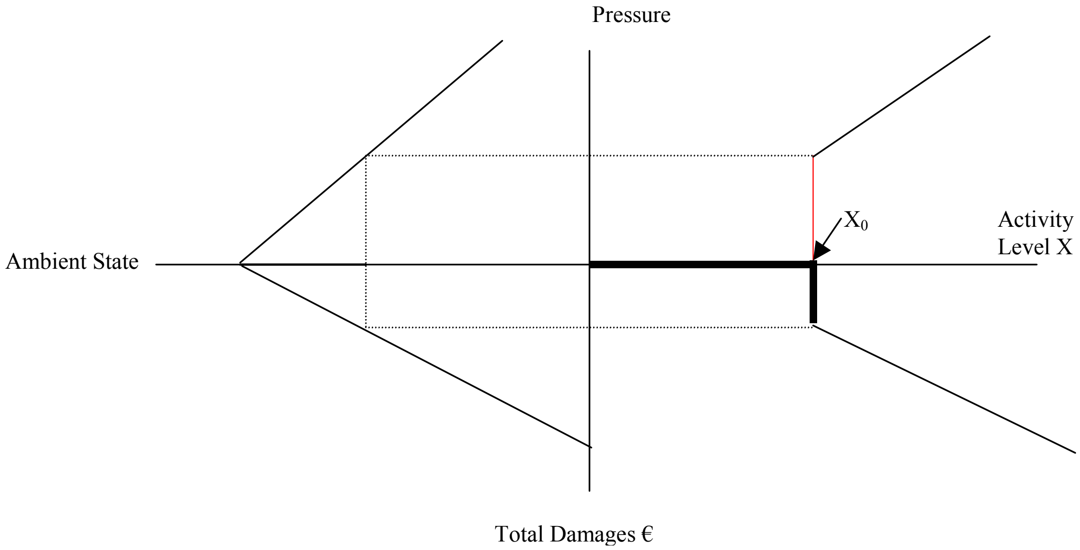


Figure 2.2 Valuation in the presence of discontinuities in the activity-pressure relationship

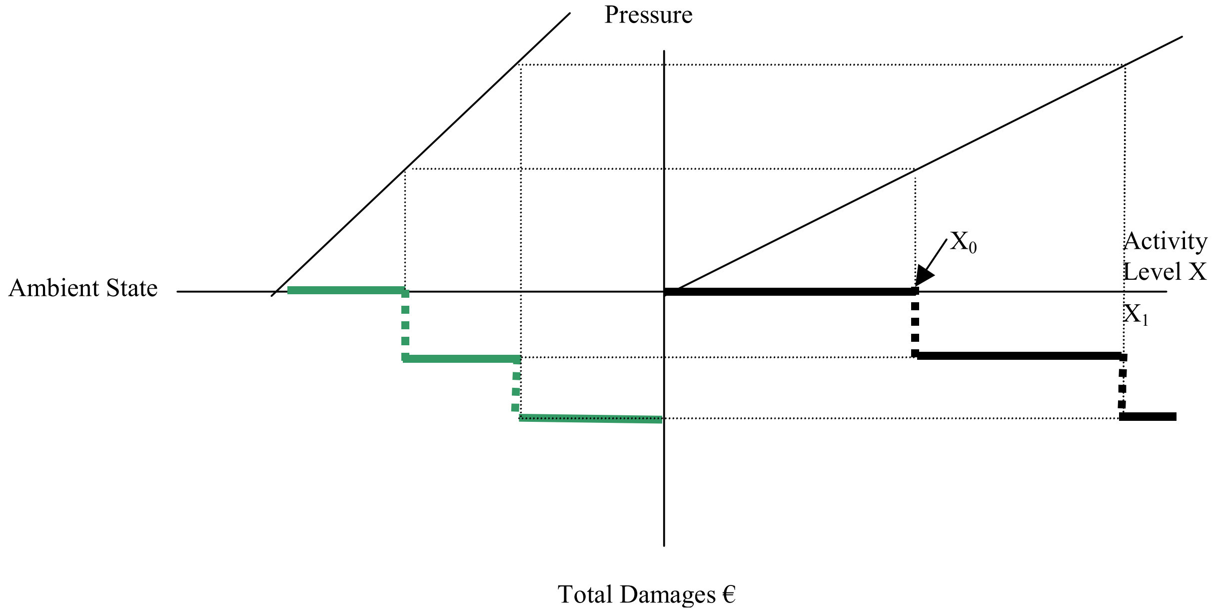


2.4. State-Valuation Relationship

In Figure 2.3 the discontinuity is in the ‘state-valuation’ relationship. This also causes a ‘jump’ in the total valuation function at the point X_0. Examples of such discontinuities are frequently found in the literature on the valuation of recreational uses according to categories that are defined for interval values of the ambient state (Bergstrom et al, 2001) – so for example water is acceptable for bathing at a lower level of pollution than water that is acceptable for other recreational uses such as fishing, boating and walking by (indicating a stepwise relationship).

These kinds of valuation function are very different from the standard externality valuation function, where every unit increase in the activity (e.g. emissions of Nitrogen or Phosphorous into a water body) is valued at a constant amount.

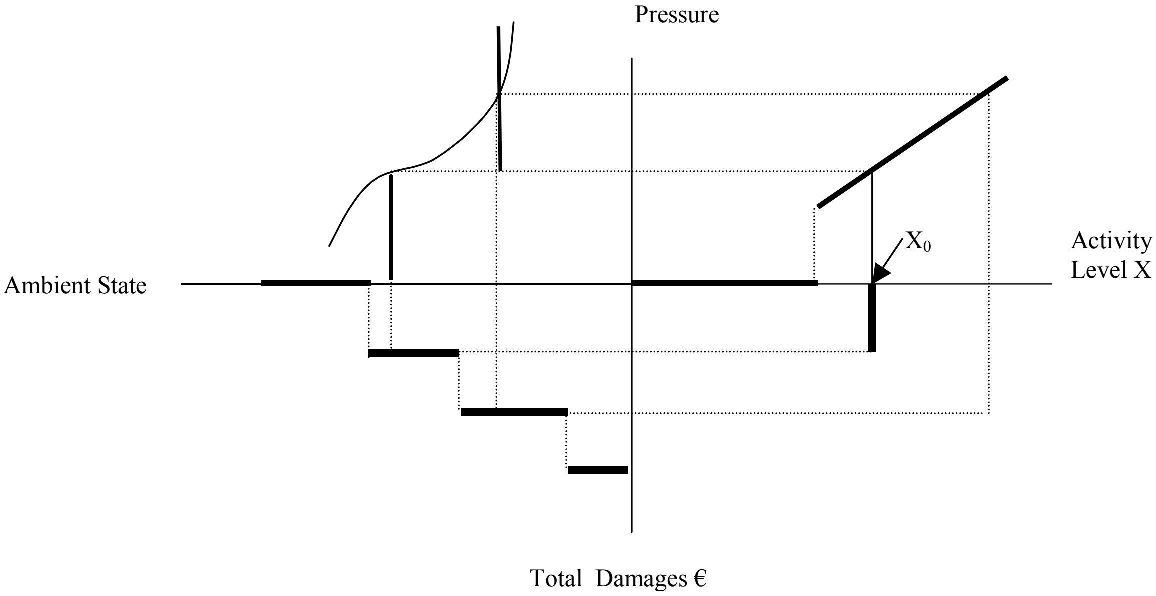
Figure 2.3 Valuation in the presence of discontinuities in the state-valuation relationship



2.5. Multiple Threshold Effects

In reality, there may be multiple threshold-type effects. This leads to an analysis such as shown in Figure 2.4 below. The inter-relationship between the threshold effects is key to the valuation – if, as shown in by the bold lines in the top left quadrant Figure 4 below, there is a step-type change in the ambient environment resulting from a change in pressure and this does not then deteriorate with increased pressure then this dominates the other changes in terms of the valuation and would be the only threshold-effect of interest to the policy maker. In reality, multiple step-functions may exist or there may be other complexities in moving from one state of nature to another (eg points of no return or hysteresis). For example, a sigmoid type pressure-state relationship would mean that other thresholds would also take effect – and this is shown by the curved line in the top left quadrant. The treatment of uncertainty and hysteresis is discussed later.

Figure 2.4 Valuation in the presence of multiple discontinuities



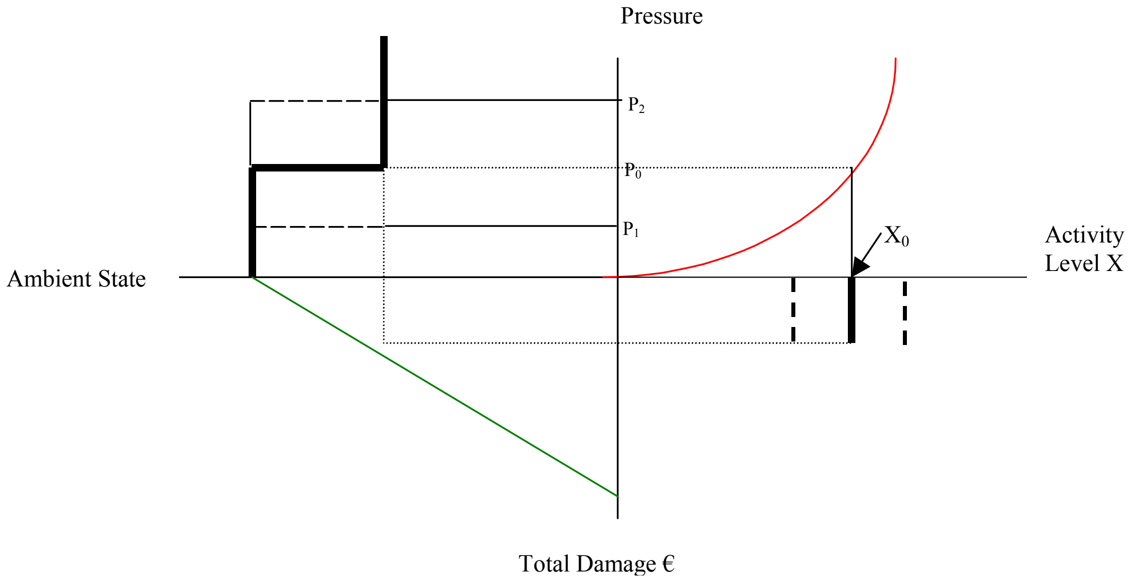
3. Developing the framework

3.1. Uncertainty

Underpinning all work on valuation of ecosystems is the concept of uncertainty. A number of uncertainties exist in the analysis. For example, we may be uncertain as to the exact level of the threshold of nutrient flow (or type of nutrient) that may lead to the growth of algal blooms. The marine ecosystem is a complex system, with a number of exogenous factors - such as climate - influencing the state of nature at any one time.

Uncertainty can be considered through introducing stochastic elements into the assessment framework developed in Section 2 of this paper. Introducing probabilities into this would lead to the consideration of expected values of different activity levels and associated environmental impacts. Figure 3.1 illustrates this. If, for example, one is uncertain as to the pressure that will lead to a change in the ambient state – but think that it lies between P_1 and P_2 then one may define loading as a distribution function rather than a deterministic value. The joint probability distribution of the outcome of interest (e.g willingness to pay for the abatement of impact for a particular activity) can then be quantified using Monte Carlo simulation of the distributions involved. Bayesian belief network models may be used to update such probability distributions as new observations become available, demonstrating the value of information in reducing uncertainty. Of course, this gets all the more complex as one adds additional uncertainties.

Figure 3.1 Valuation in the presence of uncertainty



3.2. Hysteresis

Marine ecosystems are characterised by a degree of hysteresis – i.e. there may be significant time lags between removing the pressure and a return to the original state of nature. The rate of time preference is normally reflected through the use of discounting. Hence, we would take the net present value of the project inputs and outputs across time. Hysteresis may also increase the difference between compensating and equivalent variation welfare measures of nutrient abatement policies on either side of the threshold (e.g. a survey of willingness to pay to avoid future nutrient loading should produce lower values than willingness to pay to reduce existing nutrient loads once the threshold has been crossed if respondents are aware of hysteresis in the system but still willing to deal with the problem). Hysteresis is shown in the top left hand quadrant of Figure 3.2 below, in that once reaching the level of P1, the return to the original state of environment is reflected by the second curve with a downward arrow, hence increased reductions in loadings are needed to encourage this reduction in this case.

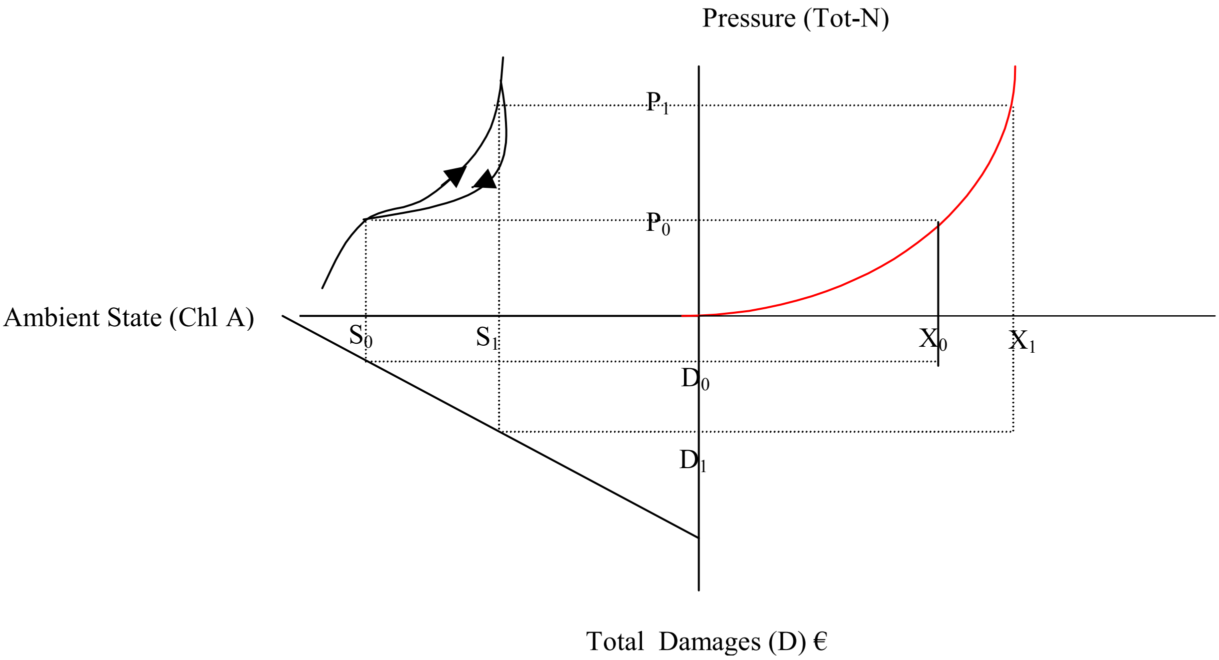
In terms of placing this value in its current present value context one could suppose that a loading of nutrients of N cause damages of €X over a period of years. If the loading is reduced below its threshold levels, damages will drop to zero, but this will only happen after T years. Then the benefits of the reduction in loading today are B, where:

$$B = \sum_{t} \sum_{t=0}^{t=T} \frac{Xt}{(1+r)^{t}}$$

Where 'r' is the rate of discount. A more complex analysis is possible but the essential point remains the same: that hysteresis will have an impact on the valuation through the discount rate.

The inclusion of this factor also throws up some interesting questions in terms of policy applications that may mirror the debate in the climate change literature on the discounting of longer term impacts. It implies a limited "policy-relevance" of restoring ecosystems to their previous state in the case of a threshold that exhibits hysteresis. This may lead some to suggest that such longer term benefits of ecosystem restoration should be considered differently to normal project impacts – e.g. through use of a different discount rate or a declining discount rate over time to promote sustainability (see eg HM Treasury Green Book which proposes this for climate change projects).

Figure 3.2 Valuation in the presence of hysteresis



4. Case Study: Algal Blooms

The link between algal blooms and nutrient loading is well established in the scientific literature. Within the context of the current *Thresholds* project, three major coastal areas will be subjected to valuation exercises on the costs of algal blooms. We now present the case of algal blooms, using the framework presented above to highlight the particularities of assessing the costs of increased nutrient load after a certain level of nutrient loading is exceeded.

4.1. Activity-Pressure relationship

The linkage between economic activity and environmental pressure in this context is a complex one. The causes of nitrogen and phosphorous entering the watersheds and being discharged to the coastal area are multiple and diffuse. Table 4.1 summarises activities that may lead to such nutrient discharge.

Table 4.1 Increased Nutrient Loads and Potential Thresholds

Cause of increased nutrient load	**Potential threshold**
Agricultural use of fertiliser	Exceeding maximum take-up of nitrogen by soil
Sewage discharge	Exceeding maximum capacity of sewage treatment plants (STPs) may lead to steeper increases in nutrient discharge
Surface erosion	Extreme weather and surface erosion may cause pulses of particle bound nutrients

4.2. Pressure-Environmental state relationship

The linkage between nutrient loads and the environmental state exhibits a large threshold effect in that algal blooms arise with increased levels of nutrients, given specific climatic and other conditions. A more complex and realistic example (from freshwater) is that while total phosphorous exhibits a linear relationship with total phytoplankton biomass(wet weight or ChlA), the fraction of cyanobacteria relative to algal biomass exhibits a threshold. Whether cyanobacteria are toxic or not depends on a number of ecological factors such as inter-species competition for light and nutrients and is an uncertainty regarding the health impacts of the threshold.

4.3. Environmental state-valuation relationship

The linkage between environmental state and valuation depends critically on the uses of the coastal zone. Table 4.2 summarises different uses of the coastal zone and highlights where thresholds may exist for algal blooms in this context.

The combination of the potential thresholds results in a relationship between the level of nutrient that could take the form shown in Table 4.3 and Figure 4.1. These illustrate the situation where the threshold levels vary by impact, resulting in a step function for the nutrient loading-damage relationship. Of course, the actual values may vary and be even more complex than shown here, but the purpose of this presentation is to show how the relationship would be estimated and put together.

Table 4.2 Potential thresholds in state-valuation relationship

Use of coastal zone	Potential thresholds
Ecosystem service – Biodiversity	Algal blooms restrict sunlight and impact on viability of existing ecosystem.
Fisheries	Certain types of algal blooms are harmful and may lead to fishing activity being banned. In addition algal blooms may have an impact on the quantity and quality of fish stocks, given that fish stocks are related to water quality.
Swimming	Algal blooms may discourage bathing. Toxic algal blooms may also lead to the banning of swimming in certain areas.
Walking	The perception of algal blooms may fall at a certain level of algal bloom coverage or at a certain distance from the bloom/sea. Odour may also arise from greater densities of algal bloom.
Amenity	Changes in perception of algal bloom may affect house prices.

Note: harmful algal blooms (HABs) are not necessarily toxic

For ease of exposition let us assume that $Z1<Z2<Z3<Z4$. The corresponding damage function will then take shape as shown in Figure 4.1. Note this makes a number of simplifying assumptions, including that all are represented by "step" functions in the valuation, which is not true in reality (e.g. marginal impacts of water clarity may exist).

4.4. Cost-benefit analysis of changes in nutrient flow and valuation of thresholds

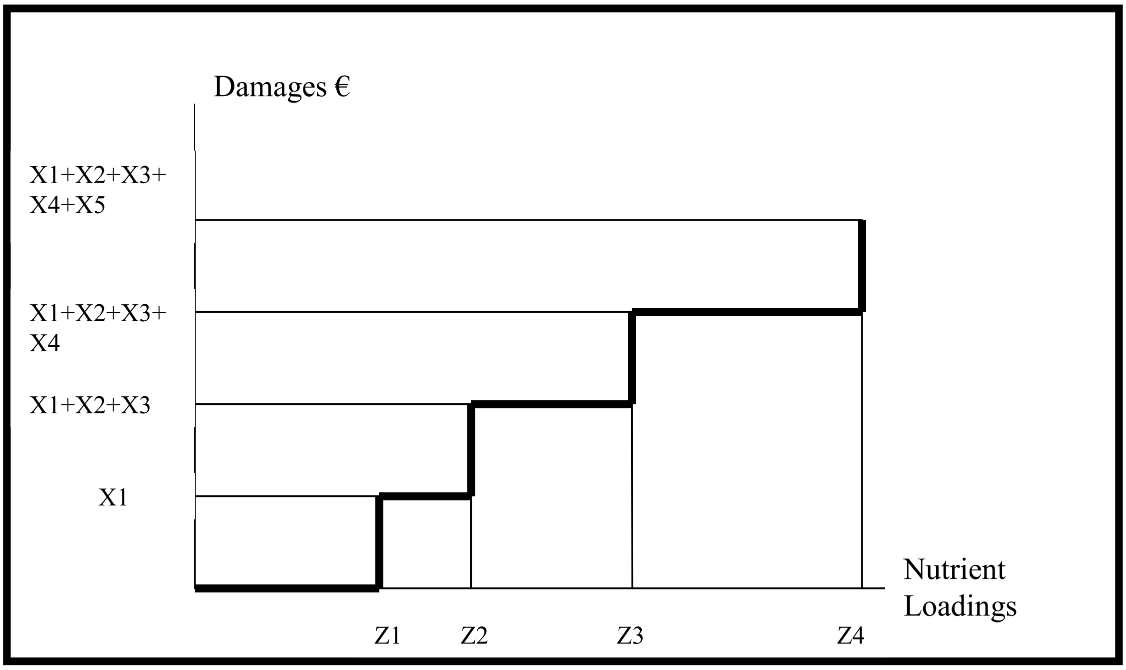
A consequence of the above analysis is that cost-benefit analysis of changes in nutrient flow need to take such threshold effects into account. This is very different from the standard environmental economics approach, which assumes linearity in the impacts and may assign a unit value to a pollutant.

To focus on the valuation of algal blooms in the context of a multi-attribute environmental problem, Table 4.3 indicates that it a combination of approaches will probably be required. A recent study for the EC combined market and non-market approaches to value the impacts of algal blooms, using CVM to estimate the impacts on tourists and market based approaches to estimate the impacts on the fisheries industry(Scatasta et al, 2003) . Among other things this study shows that thresholds also need to be considered in the valuation of ecosystem services. To a certain extent these have been in terms of changing water quality indices and recreational uses (see eg FWR, 1996; Markandya and Tamborra, forthcoming) but the linkage to activity and pressure is often poorly defined. Further work as part of the EC-funded Thresholds will attempt to develop these linkages for marine eco-systems, including a contingent valuation of algal blooms in three areas: Mallorca, the North Sea and the Black Sea.

Table 4.3 The Pathway from Thresholds to Valuation

Use of Coastal Zone	**Threshold**	**Valuation of Impact**	**Valuation of Activity**
Ecosystem Services	Blooms above a certain density may be damaging to certain ecosystems	CVM, which define the losst services and then ask individuals their WTP to avoid those losses. Or we can value the loss of services provided by the ecosystem. Estimated damage = €X1	Once nutrient loadings reach a level Z1 that exceeds the threshold density a damage of €X1 will be associated with them. Further increases may cause a zero additional damage
Fisheries	Toxic algal blooms may lead to a ban on fishing, and shellfish and mollusc harvesting	Loss of commercial value of fisheries using market valuation methods. Loss of recreational fisheries using travel cost or CVM methods. Total damages estimated at €X2	Once nutrient loadings exceed a certain level Z2, blooms form these damages occur. So the damage value attached to increases above that level is equal to €X2 for fisheries and €X3 for swimming. Further increases may cause a zero additional damage
Swimming	Algal blooms make bathing less attractive. Some HABs may also lead to the banning of swimming in certain areas.	Valuation will be based on CVM methods, eliciting the WTP to avoid these blooms. Total damages estimated at €X3	
Walking	The perception of algal blooms may cause a fall in the pleasure from walking at a certain level of algal bloom coverage. Odour may also arise from greater densities of algal bloom.	Valuation will be carried out using CVM methods – see above. Damages estimated at €X4.	The nutrient loadings required to give rise to these damages may be different from those required to cause the fisheries and swimming losses. Let us assume it is level Z3. But the principle is the same: damages equal to €X4 arise once threshold is breached and there are zero additional damages thereafter.
Amenity	Algal blooms may cause a loss of property values	Valuation would be based on the 'hedonic' method – i.e. linking the fall in house prices to the presence or absence of algal blooms. Damages estimated at €X5.	Damages of €X5 will arise once the threshold level of nutrient loadings Z4 is exceeded. Further increases in loadings cause zero additional damage

Figure 4.1 Nutrient loadings and damages (simplified)



5. Conclusions

Marine ecosystems provide a variety of services and are subject to a range of pressures on their ambient quality. This paper has presented a taxonomy for the different types of non-linearities or thresholds that may exist, highlighting three main forms of thresholds: pressure-ambient state; activity-pressure and valuation-ambient state. It presents an overview of the literature in this area and gives a case study of the valuation of the impacts of algal blooms. Finally, the framework is developed to include both uncertainty and hysteresis, which are important in the context of coastal zones. Further research includes applying this framework to three coastal zone areas within the Thresholds project – notably the North Sea, Black Sea and Mallorcan coast.

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