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# Uncertainty and the Active Adaptive Management of Marine Reserves

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Unpredictable environmental fluctuations are a major problem in fisheries. To mitigate these uncertainties, reserves are advocated to help ensure population persistence, reduce population and harvest variance and to provide a 'hedge' against management failures. Using recent insights from the modelling of marine reserves that indicate that reserves can generate a 'win-win' in terms of economic payoffs and ecological benefits, we propose a six-step process for managing reserves with uncertainty and argue in favour of initially establishing less than desirable reserve sizes where stakeholder resistance to reserves may be preventing their implementation.

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# Uncertainty and the Active Adaptive Management of Marine Reserves

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**Abstract**
Unpredictable environmental fluctuations are a major problem in fisheries. To mitigate these uncertainties, reserves are advocated to help ensure population persistence, reduce population and harvest variance and to provide a 'hedge' against management failures. Using recent insights from the modelling of marine reserves that indicate that reserves can generate a 'win-win' in terms of economic payoffs and ecological benefits, we propose a six-step process for managing reserves with uncertainty and argue in favour of initially establishing less than desirable reserve sizes where stakeholder resistance to reserves may be preventing their implementation.

**Short title:** uncertainty and marine reserves

*Key words:* marine reserves; uncertainty; adaptive management

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*Most principles of decision-making under uncertainty are common-sense …consider a variety of possible strategies; favor actions that are robust to uncertainties; hedge; favor actions that are informative; probe and experiment; monitor results; update assessments and modify policy accordingly; and favor actions that are reversible.*

Ludwig, Hilborn and Walters (1993, p. 36)

## 1. Introduction

Uncertainty conveys our ignorance to both model and predict the state of nature. In fisheries, arguably the greatest uncertainty is in the form of temporal variations in populations, sub-populations and cohorts of species. These fluctuations may be random, inherent in the population dynamics or be generated by when, where and how fisheries are exploited, or may be explained by a combination of all these factors.

In the past decade, scientists and managers have argued for the greater use of marine reserves to help address uncertainty and ensure the sustainability of fisheries (Botsford, Castilla and Peterson 1997, Pauly *et al*. 2002). By creating 'no-take' areas, populations of exploited species can increase due to reduced fishing mortality and then act as a source to harvesting areas. Empirical evidence shows that reserves can increase the spawning biomass and mean size of exploited populations (Gell and Roberts 2002), population abundance (Côté, Mosquiera and Reynolds 2001) and population density, biomass, fish size and diversity (Halpern 2003). Increased abundance within reserves can also lead to positive spillovers in harvested areas as fish migrate from reserves to adjacent locations (Roberts *et al.* 2001, Gell and Roberts 2003). Reserves may also lead to a more desirable population structure (characterised by age, gender or individual size) that can also result in increased breeding success and higher mean recruitment into the harvested population (Bohnsack 1998, Jennings 2001).

In this paper, we focus on the potential benefits of marine reserves in mitigating uncertainty and the policy implications for the design and establishment of reserves. First, we present key results from the literature on marine reserves with uncertainty that suggest appropriately designed reserves can generate a 'win-win' in terms of both ecological and economic benefits. Second, we propose a six-step decision and active adaptive management process to help manage the uncertainties in determining the size, location, number and duration of reserves. Third, we examine the implications of recent insights into marine reserves for their establishment. Our conclusions emphasise the importance of stakeholder participation and adaptive processes in the design of marine reserves for fishery purposes.

## 2. Marine Reserves with Uncertainty

A key idea from biology is that the larger is a population and the less negative shocks are propagated over spatially heterogeneous sub-populations, the less likely is a given population to go extinct from environmental or demographic fluctuations (Shaffer 1981). Lauck (1996) and Lauck *et al.* (1998) were the first to model these ideas in relation to marine reserves. Their work shows that the less control managers have over setting a desired harvest rate, or the greater the level of ignorance about the actual exploitation rate, the more valuable is a reserve in its ability to ensure population persistence.

Lauck *et al.* (1998) show that setting a smaller harvest rate without a reserve is not sufficient to prevent extinction if the uncertainty is great enough. Moreover, they find that a reserve may actually increase the "guaranteed' catch as it allows for a greater exploitation rate in the harvested area because of the assurance a reserve provides against management failure. Based on simulations, they conclude that reserves need to be 50% or larger of a defined habitat to ensure population persistence.

Doyen and Béné (2003) also examine the relationship between uncertainty, defined as the difference between the actual and targeted harvest rate and marine reserves. They confirm the earlier work of Lauck *et al.* (1998) and show that reserves can simultaneously increase population persistence and raise the "guaranteed" harvest with uncertainty. In particular, they derive a critical minimum threshold level of uncertainty above which a reserve is necessary to ensure the fishery remains above its minimum viable level. They also show that the higher the target harvest rate, the lower is the uncertainty threshold. Their result supports an earlier derivation by Mangel (1998) of a "no-take invariant" with an uncertain harvest rate, where the higher is the maximum harvest level the larger the reserve size required to ensure a sustained harvest.

An important result from the literature is the ability of reserves to reduce the variance of the population and the harvest if they are subject to negative shocks. Conrad (1999) finds that harvesting increases the variance of exploited populations relative to the populations in reserves and also shows that the smaller is a reserve the less its ability to reduce the population variance. Similar conclusions have been derived by others using different models. For instance, Sladek Nowlis and Roberts (1998) and also Mangel (2000) find that reserves can reduce the variance in the harvest while Hannesson (2002) obtains this result where random environmental effects are modelled by a Wiener process in the population growth equation. Although this strengthens the case for marine reserves, Hannesson (2002) argues that reserves alone may achieve little in terms of generating economic benefits.

One of the most recent papers (Grafton, Ha and Kompas 2004) on reserves incorporates two forms of uncertainty: *environmental stochasticity* through a Wiener process that can be both positive and negative, and *negative shocks* through a Poisson process with a given probability. Using a perturbation method (Judd 1999) they develop, they solve for an optimal reserve size by determining the optimal harvest trajectory and then select the reserve size from 0 (no reserve) to 1.0 (no harvesting) that generates the highest discounted net economic return. They identify a 'resilience effect' (Pimm 1984), that monotonically increases in reserve size and occurs whenever the magnitude of a negative shock is equal to or greater for the harvested than for the reserve population. This effect allows both the exploited population and the harvest to recover more quickly following a negative shock. Resilience comes from the ability of reserves to act as buffer following a shock that, in turn, helps harvested populations recover faster because lower population densities in harvested areas encourage the transfer of fish from reserves to exploited areas. Under a wide range of parameter values, they show that a reserve size greater than zero will maximise the discounted net returns from fishing.

The Grafton, Ha and Kompas result is important because, in their model, the fishery is never subject to extinction, the fishery is harvested optimally and the benefits of a reserve are independent as to whether the resource is initially overexploited or not. In other words, with uncertainty, reserves generate economic benefits that cannot be obtained with effort or output controls alone even if they are set optimally, and are quite apart from any payoffs they may deliver in helping to ensure a persistent population.

Their work also generates another useful insight that has important policy implications. Namely, the sum of the discounted net returns from fishing is strictly concave in reserve size. This holds true for any parameter values, provided it is economically optimal to have a reserve. The immediate significance of this result is that any reserve less than its positive optimal size yields a higher economic return than having no reserve. Thus, with uncertainty, and contrary to the existing literature (Hannesson 1998), it is not necessary to have a large marine reserve to generate economic benefits to fishers.

## 3. Active Adaptive Management of Marine Reserves

Marine reserves mitigate environmental and demographic fluctuations by providing options in the face of severe declines in stock size (Grafton and Silva Echenique 1997) that are robust to uncertainty (Ludwig, Hilborn and Walters 1993). The key decision variables faced by policy makers regarding marine reserves: their number, size, location and duration, also generate their own uncertainties. For example, determination of the location of reserves requires an understanding of fisher behaviour (Wilen *et al.* 2002), as well as an appreciation of biological and productivity criteria of different habitats (Roberts *et al.* 2003). The size of reserves is influenced by many variables, such as our understanding of dispersal rates and the directional spreading of population sources (Gaines, Gaylord and Largier 2003), the growth rate of targeted species, and the relationship between key reserve benefits (biodiversity, population abundance, etc.) and reserve size. The determination of the number of reserves depends on various relationships including the likelihood of negative shocks by spatial area and the ability of shocks to propagate between reserves and harvested areas. The duration of the reserve also depends on several unknowns, such as transfer rates between reserves and harvested areas and the effects of crowding within reserves (Béné and Tewfik 2003).

Active adaptive management, first introduced into fisheries by Walters and Hilborn (1976), and elaborated on by Walters and Hilborn (1978) among others, is a process to improve management given uncertainties. The key point of active adaptive management is that it involves a *process* of active learning, planning, evaluation and judgment about the socio-economic-ecological environment and the effects of key decision variables. Active adaptive management implies that one-shot or one-off attempts to optimally set the size, number, location and duration of reserves are sub-optimal. In part, this is because fisheries managers frequently lack either the knowledge or data to construct meaningful spatial models of reserves and connections to harvested areas (Holland 2002). However, even in the best-case scenario where managers have all of the true models of the population and source-sink dynamics, with correct parameter values, irreducible uncertainties still remain because of the inability to predict the future. Thus managers will always remain in a second-best world and the best they can do is to establish a decision-making process that will help them optimise in the face of uncertainty.

Adaptive decision processes that help mitigate uncertainty in marine reserves have existed for a long time. For example, traditional ecological knowledge has been used in the design of marine reserves in community fisheries for centuries, or more, and is characterised by feedback learning and hedging of management strategies (Berkes, Colding and Folke 2000). We build on these existing ideas, and the recognition that adaptive management has an important role to play in the design of marine reserves (Smith and Pollard 1996, Sale 2002), to propose a six-step decision, learning and feedback process for reserves. This process informs marine stakeholders (Mikalsen and Jentoft 2001) and guides decision makers to adapt to changes in their understanding of the environment and states of nature. It does so by evaluating the current level of the decision variables and modifying them, as necessary, in a feedback loop to achieve management objectives.

We formalise the process of active adaptive management of marine reserves with six general steps that are illustrated in Figure 1. *Step one* specifies the objectives and begins the feedback loop for marine reserve design, for without a clear understanding as to what reserves should accomplish, there can be no adaptive management of reserves. To be of use to managers, the goals need to be measurable and be developed, discussed and agreed to by key stakeholders in the fishery. Where more than one objective is defined then a prioritisation or weighting of goals is required should tradeoffs between objectives be necessary.

*Step two* is a socio-economic-ecological system appraisal. The time and effort spent on the appraisal will vary according to the expected importance of the possible changes in key variables governing marine reserves. For example, the recent and very substantial enlargement of the use of reserves in the Great

Barrier Reef in 2003 by the Australian Government involved a major appraisal of a multitude of factors and many thousands of submissions from interested parties (Dickie 2003). Establishing a very small reserve not frequented by commercial or recreational fishers would, by comparison, require far fewer appraisal resources. At a *minimum*, an appraisal requires a description of what are considered to be important drivers of the system (ocean currents, species composition, harvesting history, etc.), the key benefits (ecosystem services, recreational, commercial, etc.) derived from the system, a description of the current and past management regime and its effectiveness and, most importantly, base-level indicators to judge the effectiveness of reserves in improving management goals.

*Step three* requires decision-makers, in consultation with stakeholders, to select appropriate socio-economic-ecological criteria that will be used in the determination of key decision variables about reserves. Ward *et al.* (2001) list 58 possible criteria that include social (wellbeing of communities), biological (biodiversity), management (lower enforcement costs) and economic outcomes (enhanced employment), among others. Whatever the criteria chosen, they must be linked back to the objectives of reserve management. For example, if species diversity is a goal then bio-geographic representation and habitat heterogeneity are necessary criteria (Roberts *et al.* 2003). If generating an economic return from fishing is a goal, the profitability of the fishing fleet might be used as a criterion.

*Step four* is arguably the most difficult part of the process for it requires that decisions be made regarding the size, number, duration and location of marine reserves. It should be emphasised, however, that the decision-making process is actively adaptive so that errors made in initially setting reserve size can be mitigated in the future through a feedback learning process. Various approaches can be used to combine the criteria and then set the key variables regarding reserve size. For example, Roberts *et al.* (2003) recommend an evaluation process that scores units of habitat area that are then ranked and selected to achieve the defined objectives.

We argue for a framework whereby the criteria developed in step three are mapped into the goals of management and then optimised using the decision variables. A recent example of such an approach is found in Beattie *et al.* (2002) who use large-scale ecosystem modelling to determine the location and size of a marine reserve size for the Baltic Sea. Ideally, such modelling should include marine reserve and fishery dynamics, especially dispersal dynamics (Gaines, Gaylord and Largier 2003) and fisher behaviour in response to reserves (Smith and Wilen 2003, Wilen *et al.* 2002). It should also allow decision makers to make judgments about trade-offs in goals and evaluate various outcomes under a range of scenarios or states of nature. Where appropriate, the framework should also include traditional ecological knowledge to better appreciate the possible feedbacks of different decisions. Indeed, in some jurisdictions traditional knowledge may be the key information source to compare various alternatives and assess possible outcomes.

In some fisheries the inability to model the effects of reserves, or the paucity of data may be such that formal models of marine reserves may not be possible. In such environments, decision makers may need to fall back on 'principles' or 'rules of thumb' to guide them in initially setting the key decision variables. A number of such rules exist including four principles by Botsford, Michelli and Hastings (2003), bioeconomic rules of thumb by Grafton, Ha and

Kompas (2004) and rules associated with the home range of fish (Kramer and Chapman 1999), among others. A synthesis of existing empirical studies and case studies of reserves (Gell and Roberts 2002, McNeill 1994) may also help guide the decision-making process.

*Step five* provides a review by peers and stakeholders of all the previous steps and should allow, where warranted, changes to the proposed decision variables. The purpose of the review is to catch mistakes or errors in judgment and is not a substitute for excluding stakeholders in the previous steps. In other words, stakeholders should be included in *every step* in actively managing marine reserves and their input incorporated as early on as possible (Langstaff 2003). Such an approach is required to develop the co-operation needed to ensure reserves meet their conservation objectives (Jones 1999). Indeed, Francis, Nilsson and Waruinge (2002) go so far as to suggest that in developing regions marine reserves cannot succeed on a long-term basis without local community support. To make the review as productive as possible, the process should only make changes to the decision variables if there is a convincing argument that such a change would lead to a superior outcome, as defined in the objectives in step one.

*Step six* requires that managers actively learn and experiment so as to have better designed reserves that meet the defined goals. The experimentation does *not* begin after the initial decision variables about reserves are determined, but should be incorporated into the decision-making process from the start. For example, if fishery managers initially do not know, or have very little idea, what places may be the best locales to situate reserves it is worthwhile to experiment by setting reserves of various sizes in different locations. Following up such a reserve design with formal analysis, such as before-after-control-impact-pairs analysis (Underwoord 1994, Russ 2002), would then provide information as to where the preferred locations might be.

Evaluation of reserves must also explicitly account for and link to other management regulations, such as effort limits or output controls that are likely to be used concurrently in harvested areas. This is because, whatever the benefits reserves deliver, it is highly unlikely that they can address all of the problems inherent in fisheries management (Allison, Lubchenco and Carr 1998). For example, without controls on fishing in harvested areas, rivalry among fishers will likely result in the dissipation of economic rents. Consequently other management approaches, such as individual transferable quotas (Squires *et al.* 1998), may be required to manage fishing in harvested areas in conjunction with marine reserves.

Another key component of the final step of the design process is to evaluate outcomes from reserves relative to the defined objectives over appropriate time horizons. For instance, if a goal is to increase the size of the spawning biomass of a harvested species, there must be procedures in place to track for changes in abundance across reserves and harvested areas. Finally, the evaluation must translate into changes in the decision and control variables, if required, and feed into periodic reviews of the objectives of reserve management. For instance, the Great Barrier Reef Marine Park zoning plan is reviewed every five years. Thus if monitoring and evaluation, for example, finds a deterioration in ecosystem integrity of the reef this should feedback into revised goals or priorities that might involve giving a greater weight to conservation goals.

## 4. Establishing Marine Reserves for Fishery Purposes

The six-step process to active adaptive management of marine reserves will not guarantee that all management objectives are realised. What it does offer, however, is a systematic decision-making process to better design marine reserves in the face of uncertainties. Given that a decade ago there were over 1300 marine reserves worldwide (Kelleher *et al.* 1995), that many more reserves have been established in the intervening years and almost all coastal nations have committed themselves to develop representative networks of marine protected areas by 2012 (United Nations 2002), such an approach is long overdue.

One of the barriers to implementing reserves in fisheries is the opposition of fishers who claim that reserves will reduce their harvests (National Research Council 2001). This perceived trade-off between conservation and economic goals, reinforced in some deterministic models of marine reserves (Gerber, Kareiva and Bascompte 2002), is a major impediment to the increased use of reserves. The most recent work on reserves with uncertainty (Grafton, Ha and Kompas 2003), however, suggests that in many fisheries no such trade-off exists. They show that *if* a positive reserve size is economically optimal, which is true under a wide range of parameters, then any reserve size less than the optimum size generates a higher return than no reserve while also generating conservation benefits.

The policy implication is that initially establishing reserves for fishery purposes of a less than desirable size, and in different locations, should help address the concerns of fishers while simultaneously resulting in higher ecological and economic payoffs than no reserves. Thus if the establishment of reserves for fishery purposes is opposed by fishers, initially implementing less than desirable reserve sizes may help overcome the barriers necessary to introduce reserves. Clearly, there would be some limit in terms of how small a reserve should be (Walters 2000) as at some point the benefits of a reserve will be outweighed by the costs of its establishment, monitoring and enforcement. Nevertheless, recent work (Halpern 2003) that synthesises results from 89 different studies of marine reserves is encouraging in terms of the conservation and economic benefits of reserves of smaller reserves. In particular, Halpern (2003, p. S126) finds that there is a linear relationship between reserve size and increases in population or biomass level. This implies that larger reserves, at least in terms of these conservation goals, generate *proportionately* the same benefits as smaller reserves.

If less than desirable sized reserves for fishery purposes were initially implemented, but within the framework of active adaptive management of reserves, key decision variables could be subsequently changed depending on management objectives and information gained from active learning, experimentation and evaluation. The point is the initial implementation of reserves at less than their desired size may help ensure greater stakeholder acceptance while still generating economic and conservation payoffs greater than having no reserve.

The overall benefit of the proposed approach to initially setting reserve size would depend on the costs of fisheries management relative to the gains from establishing reserves. Reserves, however, are likely to be a low cost method of managing fisheries relative to effort and output controls. Indeed, Murawski *et al.* (2000) in reference to 'no-take' areas off the Georges Bank in the eastern

United States, observe that year-round closures of large areas are easier to enforce than smaller and seasonal closed areas. Another advantage to initially setting less than optimal reserve sizes for fishery purposes is that it would give fishery managers the opportunity to co-ordinate reserves with existing fisheries regulations, and thus help overcome "teething" problems with reserves at a lower cost. Increased stakeholder co-operation in the establishment of reserves should also assist in reducing the costs of enforcement (Farrow 1996).

## 5. Concluding Remarks

Marine reserves are increasingly being viewed as a means to help mitigate uncertainty in fisheries. Despite a burgeoning literature on reserves and their value with uncertainty, many policy makers lack an adaptive and systematic decision-making process to establish reserves and evaluate their costs and benefits. To overcome this gap, we provide a six-step approach for the active adaptive management of marine reserves that involves; one setting of measurable objectives, two, a socio-economic and ecosystem appraisal that occurs prior to the establishment of reserves and regularly thereafter, three, the selection of ecological and socio-economic criteria that help decide the levels of reserve size, number, location and duration, four, a framework to decide on the levels of key decision variables about reserves, five, a peer and stakeholder review of the reserve design decisions and, six, active learning, experimentation and evaluation to review the design process and ensure goals are met.

Insights from the most recent work of marine reserves with uncertainty indicate that there need not be a tradeoff between conservation and economic objectives, provided that reserves for fishery purposes are established at equal to or less than their economically optimal size. The implication is that where there is stakeholder opposition that prevents the creation of marine reserves, it may be worthwhile to initially establish reserves for fishery purposes smaller than initially desired. Such an approach should help overcome opposition to reserves, especially by fishers, while still generating greater economic and conservation benefits than no reserves. The six-step adaptive process could then be used to subsequently adjust reserve design to more optimal levels as more information is gathered and after the benefits of reserves are demonstrated to stakeholders. Overall, the proposed processes for establishing marine reserves should increase both the acceptance and use of marine reserves while also improving overall fisheries management.

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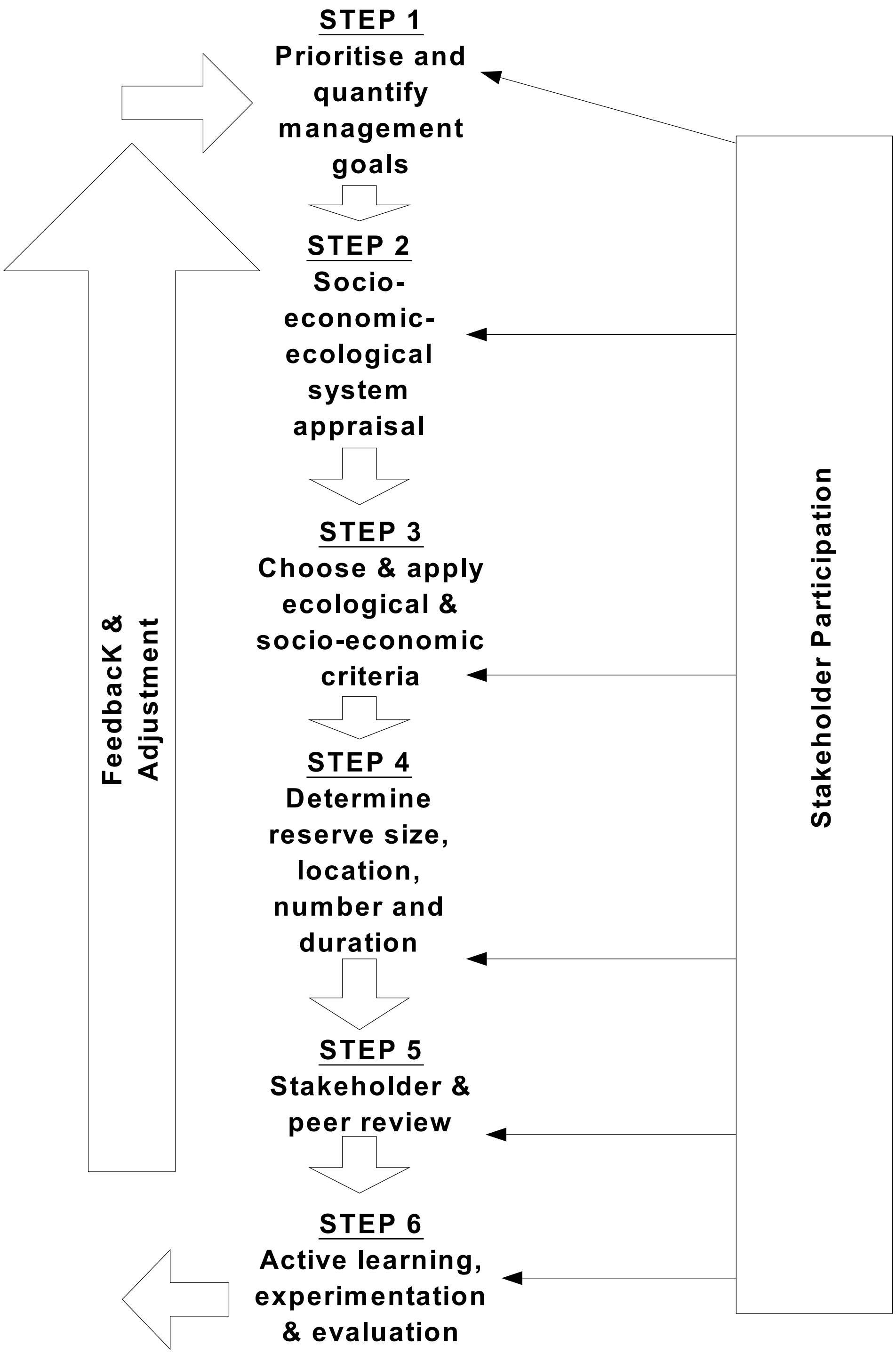


**Figure 1: Six Steps for Active and Adaptive Management of Marine Reserves**