A BIO-SOCIO-ECONOMIC SIMULATION MODEL FOR MANAGEMENT OF THE RED SEA URCHIN FISHERY IN CHILE

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for the degree of Doctor of Philosophy

by

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ORIGINALITY STATEMENT

I declare that the work contained in this dissertation is my own, and where the work of others has been used it has been properly cited. No part of this work has been submitted for any other degree.

Candidate:

Luis Matías del Campo Barquín

30 October 2002

DEDICATION

To my family.

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ABSTRACT

This study focused on the management of the red sea urchin *Loxechinus albus* fishery in Chile. The main objective was to design, construct, implement and assess a computer-based simulation model to analyse the biological effects, socio-economic consequences and spatial dynamics resulting from coastal management plans applied to this resource under the system of AMEBR. This was accomplished by using systems dynamics (SD) and geographical information systems (GIS) modelling, in a process of model development, run, optimisation, sensitivity analysis and risk management, and a series of field-based activities carried out at the cove of Quintay.

The GIS model developed for allocating sea urchins restocking sites offered a flexible, cost-effective, user-friendly and descriptive technique for support decision-making on management of this species and other benthic resources. Final site selection for restocking was based on the identification, quantification and selection of higher suitability¦availability combinations (site categories). This map showed 16 different suitability¦availability combinations or site categories, ranging from 4¦100 to 8¦100 (suitability points¦availability %). These had an average of 6.44¦69.37 (covering an area of 82.5 Ha overall equivalent to 81.21% of the study area. This site classification demonstrated high heterogeneity between options, and revealed the full variety of alternatives for decision-making. More importantly, the generally high suitability indexes as well as available area emphasised the prospects for restocking sea urchins in this study area.

Over and above of the quantitative outcomes obtained from running the GISRM (suitable and available restocking sites) and the BSESM (alternative strategic management plans), the case study-based analysis made it possible to disclose the wider issues related to the red sea urchin coastal management.

These results demonstrated the biological inefficiency of traditional size/seasonal restriction-based approach (macro-scenario 1) for sustainable management of the target species. More importantly, final outcomes strongly suggested that a combination of adaptive restocking-based enhancement activities and flexible exploitation constituted a highly attractive approach (macro-scenario 3) for stock management of this fishery in terms of harvestable stock and related incomes.

However from the economic analysis, stocking was also found to be economically unfeasible, being a rather cost intensive exercise negatively affected by high natural mortality rates. A single-variable optimisation analysis demonstrated that a higher survival rate is needed to generate sufficient profits to cover major restocking costs and a positive payment, or a cost reduction is essential to make up for the loss.

On top to these practical constraints, based on the distinctive modest economic situation prevailing for most Chilean coves and hence their limited capacity to pay for stocking material, unless adequate and constant funding is available to support artisanal associations, they are very unlikely to develop mass release programmes.

Given the economic (i.e.: high operating costs) and technical (i.e.: low survival rates) limitations conditioning stocking-based management cost-effectiveness and applicability, wide implementation of mass releases as a major approach for management of the red sea urchin fishery is very unlikely to take place in Chile.

This study presents a methodology and offers a tool to design, evaluate and optimise coastal management plans for the red sea urchin in a dynamic, interactive, systematic, integrated and flexible way. The optional strategic management plans proposed on this study may not be applied equally to any AMEBR, as they are the outputs arising from a single cove-specific analysis. Still, the complete methodological framework and analysis procedures developed may be applied to run the BSESM and optimise management of a red sea urchin fishery at any other AMEBR case of study.

CHAPTER 1

INTRODUCTION

1.1 THE STATE OF WORLD MARINE FISHERIES

"Current increasing rates in world population are calling into attention human capacity to provide a sufficient quantity of food for all into the next century" (Welcomme, 1996). Despite the impressive growth through the 1970`s and the 1980`s, agricultural activities have shown relative stagnation more recently (FAO, 1993). In such a context, aquatic products constitute an important component in world food supply (UNDP, 1994). However, after increasing development during the last two decades, the world's fisheries sector is following the same pattern of stagnation as most other food production activities (Welcomme, 1996). Likewise, "fisheries are becoming limited by physical and biological capacity, by deteriorating environments, and by resource costs of excessive levels of exploitation" (Muir, 1996).

For the world as a whole, landings of marine fish are continuing to level off. This is the general trend for most major fishing areas, where fisheries have evolved from a phase of increasing fishing effort and production to one in which production has stagnated and in some cases declined. Judging from known fish stocks and resources of traditional fisheries, the total marine catches from most of the main fishing areas in the Atlantic Ocean and some in the Pacific Ocean would appear to have reached their maximum potential some years ago, and substantial total catch increases from these areas are therefore unlikely (FAO, 1998). Though aquaculture may be expected to assume an increasingly important role in the management of currently exploited stocks, the use of historically underexploited stocks, and the possible enhancement of key resources, are to become crucial in ensuring the long-term ability to supply aquatic products.

1.2 MARINE RESOURCES IN CHILE

The Chilean marine and freshwater resources are based on large-scale (industrial) fisheries, small-scale (artisanal) fisheries and aquaculture production. During the last twenty years, these three components have experienced spectacular growth in landings and revenues (Castilla, 1997). Nevertheless, during the 1990's this trend was not observed, and despite a few peaks in specific periods (1994 and 1995), total landings and revenues appeared to maintain volumes relatively level or slightly decreasing (Fig. 1.1).

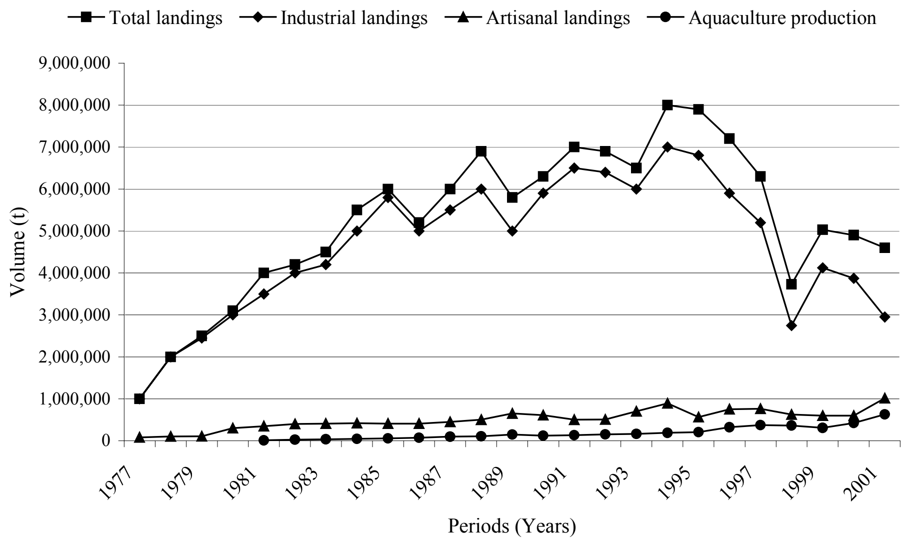


Figure 1.1: Total landings of the Chilean industrial, artisanal fisheries and aquaculture production between 1977 and 2001 (Servicio Nacional de Pesca, 1987; 1997; 2001).

In global terms, fishing has become an important commodity in trade in Chile (Castilla, 1997). The total net export value from industrial and artisanal fisheries, and aquaculture, has steadily increased from U$100.6 millions in 1976 to a peak of U$1,892 millions in 1997 (Castilla 1997; ProChile, 2002). Chilean fisheries provided with nearly 10 million t of fish, molluscs, and crustaceans in 1996, accounting for 6% of world production and 35% of total fish production (ProChile, 1999). In 1999, Chile exported U$108.90 million of molluscs, crustaceans and echinoderms, primarily sea urchins, octopus, and scallops, to the world (ProChile, 2002).

1.3 SMALL-SCALE FISHERIES

Although large-scale fisheries have always been focus of attention for biology and management, small-scale fisheries are also very important. Particularly in developing countries, like Chile, a large group of fin fisheries and shellfisheries is operated at a small-scale (Castilla and Fernandez, 1998). As defined by Aguero (1992) small-scale fisheries include:

- Fisheries operating with "open boats" of <50 t such as engine-powered (inboard, outboard) boats, or rowboats.
- Fisheries based on diving operations, or on handpicking procedures on shore.

The importance of artisanal fisheries in Latin America relies on the fact that more than one million people are directly related with fishing activities, of which at least 90% belong to the small-scale sector (Aguero, 1992). This sub sector is mainly sustained by pelagic, demersal and benthic species, limited to inshore coastal areas (Table 1.1) (SERVICIO PAIS, 1998), and mostly endemic species with restricted geographical distributions or unique to the area (e.g. Bustamante and Castilla, 1987). Likewise, this sub sector provides the bulk of domestic daily food, while several species extracted, such as shellfishes, echinoderms and algae, have high market values as compared to products fished by industrial fleets (Castilla and Fernandez, 1998).

Although the landings of the industrial fleet in Chile (>$6*10^6$ t/year) substantially overpasses artisanal landings ($1.5*10^5$ t/year), more than 60 species of shellfish and algae are regularly exploited exclusively by small-scale fishery sector (Castilla, 1997; Castilla and Fernandez, 1998). In general, this activity is based on diving operations (Castilla, 1988; Aranda *et al*., 1989; Castilla, 1997).

Table 1.1: Coastal resources supporting small-scale fishing activities in Chile (SERVICIO PAIS, 1998).

Group	**Description**
Pelagic	Organisms that inhabit and use the surface and sub-surface of the sea, forming large shoals, e.g.: “sardina española”, “sardina común”, “jurel”, “caballa” and “bonito”.
Demersal	Organisms that inhabit near the bottom during their adult stage and depend on substrate for some vital functions, e.g.: “merluza”, “merluza”, “congrio”, “raya”, “toyo”, and “corvina”.
Benthic	Organisms that have high dependence on the bottom, e.g.: “jaiva”, “centolla”, “almeja”, “macha”, “cholga”, “chorito”, “erizo”, “lapa”, “loco”.

Artisanal fisheries activities based on benthic resources in Chile have traditionally exploited high-value products for direct consumption (Gonzalez, 1996; SERVICIO PAIS, 1998). Among these, the main commercial resources are: the “loco”-abalone *Concholepas concholepas*, the red sea urchin *Loxechinus albus*, keyhole limpets *Fissurela* spp., crabs *Homolapsis plana* and *Cancer setosus* and “macha” clams *Mossodesma donacium*.

The importance of these fisheries in Chile also relates to socio-economic reasons. According to Subsecretaria de Pesca (2000c), in 1999 there were approximately 11,000 small-artisanal vessels and more than 12,000 registered divers and 6,000 collectors. Additionally, it is estimated that this sector provides employment to over 70,000 fishermen distributed in 425 small coves or ‘caletas’. The annual shellfish landings range between

140,000 and 160,000 t, representing 2% of total landings and a peak export value of U$ 140 million (11% of total revenue) in 1994.

When analysing the trend on artisanal landings fisheries (Fig. 1.2) is possible to distinguish two phases: the first representing almost exclusively domestic consumption, with volumes ranging between 70,093 t (1968) and 128,558 t (1978); and a second with rising exports, where landings increased to 274,352 t (1979) (Castilla, 1997) and reached a peak of 969,524 t in 1996. Thereafter, with the exception of 1999, total landing volumes have steadily decreased to reach a level of 497,266 t in 2000.

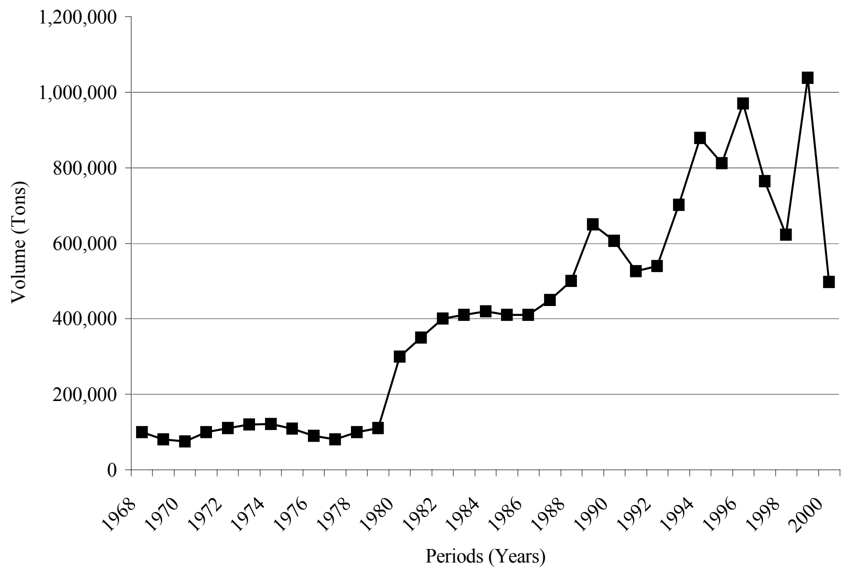


Figure 1.2: Total artisanal landings in Chile between 1968 and 2000 (Servicio Nacional de Pesca, 1978; 1988; 1998; 2000).

Although the capacity of artisanal fishing units may be limited, resources targeted by small-scale fisheries in Chile are not immune to overexploitation. In fact, they have described the same pattern as large-scale fisheries, showing a clear state of depletion on a large portion of its constituent species (Castilla and Fernandez, 1998). From the early 1980’s to the present, the open-access conditions applied to Chilean fisheries in conjunction with the opening of new markets, high prices and low operational costs produced high exploitation pressures (Bustamante and Castilla, 1987; Oliva and Garrido, 1994; Castilla, 1995; Gonzalez, 1996; Castilla, 1997). In this context, according to the GFAL (General Fisheries and Aquaculture Law of Chile) fishing of these resources has reached such a level of exploitation, that beyond the harvest of authorized fishing units, there is no surplus in productive capacity. Critical limits are now being approached, and several coastal stocks are badly depleted.

1.4 THE CHILEAN RED SEA URCHIN (*LOXECHINUS ALBUS*)

The red sea urchin *Loxechinus albus* (Equinodermata: Echinoidea: Echinidae) (Fig. 1.3) is the only echinoderm specie extracted along the Chilean coast and one of the most important benthic resources for artisanal fisheries.

Figure 1.3: Chilean red sea urchin commercial size individuals and fresh product (gonads).

The natural distribution of *L. albus* is restricted to the coasts of Peru and Chile (Fig. 1.4), from Island "Lobos Afuera" (6°S in the northern extreme of Peru) to the extreme south of Chile ("Canal de Magallanes (54°S)) (Bernasconi, 1953, Larrain, 1975).

This specie presents separated sexes without external sexual dimorphism. Furthermore, it has an annual reproductive cycle (Fig. 1.5) and reaches the sexual maturation at the size of 40 to 50-mm (Castilla, 1990). Because of the size of the gonads it is not fished before it reaches 60 to 70 mm of diameter, after 3 to 5 years. Furthermore, it has external fertilization with development of short-life equinopluteus larvae.

Figure 1.4: Geographical distribution of the red sea urchin *Loxechinus albus.*

Loxechinus albus is essentially herbivorous (Dayton *et al.* 1973; Lawrence 1975; Castilla and Moreno, 1981) and feeds on macro- algae not having specific preferences (Bay-Schmidt, 1977; Buckle *et al.,* 1977). This species has a particular feeding strategy based on the capture of small pieces of macro- algae detached from the rocks (Lepez, 1988).

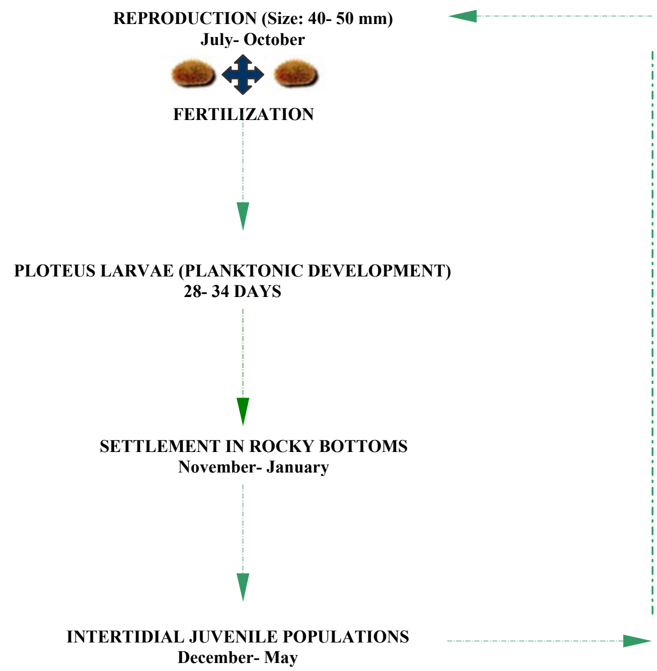


Figure 1.5: Life Cycle of *Loxechinus albus* in the central coast of Chile (modified from Castilla (1990)).

The Chilean red sea urchin is considered a non- abundant and elite edible product, therefore highly attractive in commercial terms. This species accounts for more than 90% of the group ‘other species’ in total landings in Chile (Subsecretaria de Pesca, 2002).

During the late 1990s Chile has been the largest producer of sea urchins in the world (San Martin 1987; FAO 1995a). Among the international markets, Japan is the world’s major market for sea urchins, its major suppliers being the US (57% of volume and 61% of value in 1997), Chile (17% and 12%), Canada (11% and 11%), China (7% and 6%), and South Korea (6% and 7%) (Court, 1999). Chile used to ship more than 70% of its sea urchin to Japan as steamed, frozen product. Now 70% or more of Chilean production exports are fresh, retail or bulk-packed, even live, and only about 30% or less is exported as steamed or other processed products (Court, 1999).

In line with the growth in production, the exploitation of *L. albus* has become progressively industrialized. This been reflected in the increasing production of various products such as frozen, dry-salted and more recently dehydrated- products. The majority of these are destined for international markets, such as Japan, United States, Argentina, Brazil and France. On the contrary, local consumption of sea urchins is mainly based on fresh product.

Fishing for sea urchins in Chile has been well developed in all the regions (I to XII Region) along the coastline. Among these, major volumes are primarily landed in the X and XII Regions, and secondarily in the IX, II, and III Regions (IFOP, 1999a).

As with artisanal landings in general, figures of total landings of sea urchins in Chile (Fig. 1.6) have shown two phases: an initial period characterized by small and constant volumes from 1960 to 1975, and a second period where strong exploitation was developed during the second half of the 70's, 80's and 90`s. During this period extractive volumes increased rapidly from 10,000 t in 1976, and reached a peak in 1995 with more than 50,000 t and U$55.5 millions in revenues.

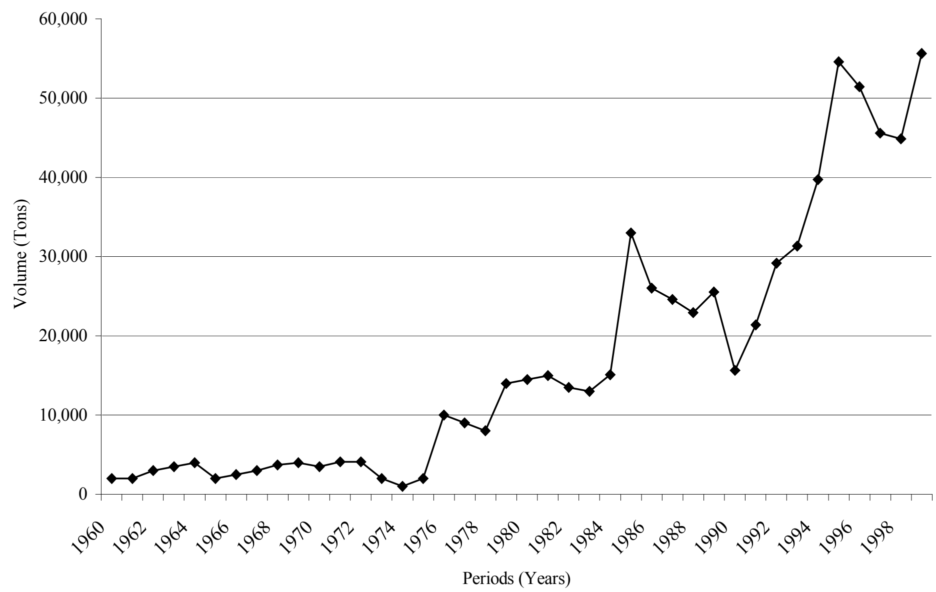


Figure 1.6: Total Landings of red sea urchin in Chile from 1960 to 1999 (Servicio Nacional de Pesca, 1970; 1980; 1990; 2000)

As Chilean production increased rapidly since 1990 after declining in the late 1980's (Fig. 1.6), overfishing and the impacts of the 1982 El Ninno event were suggested as the causes of the then declining patterns (Vasques and Guisado, 1992). Examination of the spatial distribution of harvest demonstrated that the recent expansion in the fishery was a product of new fishing ground being opened rather than through recovery of traditional fishing areas (Keesing and Hall, 1998). As most southern banks (X Region) became overexploited, fishing moved further south, most recently into the XII Region. Though contributing to more than 50% of total landings in 1995 and 1996, catches in Region XII have also started to level off. Furthermore, it is not known whether further significant, but unexploited grounds remain in Chile (Keesing and Hall, 1998).

Based on this analysis and together with information from fisheries agents (governmental agencies, fishermen associations) no doubts remain about the fact that this highly appreciated resource has clearly been severely overexploited (Gutierrez and Otsu, 1975; Bay-Schimidt, 1977; Deppe and Viviani, 1977; San Martin, 1987; Castilla, 1988; 1990; Oliva and Garrido, 1994; Paredes, 1988; Stotz *et al.*, 1992; Gonzalez, 1996; Castilla, 1997; Barahona and Jerez, 1998).

Consequently, natural stocks in several locations are highly deteriorated, even depleted, and recruitment processes diminished, therefore making natural recovery practically impossible. Given the history of this and other sea urchin fisheries it is very unlikely that catches can be sustained at this level (Keesing and Hall, 1998). Therefore considering the critical long-term socio-economic implications and current environmental situation, the red sea urchin is in urgent need of more rational management and effective recovery plans.

1.5 MANAGEMENT OF COASTAL RESOURCES: TRADITIONAL REGULATIONS V/S STOCK ENHANCEMENT

Two major approaches can be used to maintain and/or recover overexploited natural stocks of marine resources- fishery regulations and enhancement programmes. Traditional systems to recover overexploited coastal resources are mainly based on fishery regulations (DuBois, 1985). The most common tools employed are (Amstrong and Ryner, 1978; Panayotou, 1982):

- *Limit access:* limitation of fishery to a defined number of production units (boats, fishermen, gear type and number).
- *Closed areas:* prohibition of fishing or extraction in spawning or other areas considered critical for the development of the species.
- *Closed seasons:* closure of a fishery during given periods of the year, basically related to peaks of breeding and spawning periods.
- *Selective harvest:* restrictions on collecting and harvesting individuals in certain stage of development (e.g.: smolting, carrying eggs).
- *Size and/or weight restrictions:* minimum capture sizes and weights varying with the species.
- *Quotas:* enforcing individual and/or total catch ceilings.
- *Economic controls:* such as taxes on effort or catch, royalties and licenses.
- *Resource allocation:* leasehold arrangements, franchises, or allocation of ownership over an area or stock.

The degree of effectiveness of these management measures is very variable, and depends on a number of factors, such as effective on-going data collection (capture volumes and effort statistics); collection of reliable data (data manipulation, report of a minimum percentage of real captures), and consideration of real world externalities (pollution, illegal foreign fishing, or loss of distant parental stocks serving to replenish local populations) (DuBoi, 1985). However, the most complex influencing factor, is that the effectiveness of these tools will vary directly with the extent they are applied, well understood and accepted by the users (fishermen's populations), and enforced by relevant institutions. On this basis, the real application and effectiveness of such methods are strongly determined by resource user perception, level of education, economic needs, and institutional or governmental capabilities to enforce and control the accomplishment of each specific management measure.

Among various enhancement activities, "restocking" has been defined as a technique whose objective is to compensate for depleted natural resources and/or the conservation of stock species threatened with extinction (Bannister, 1991; Welcomme, 1998). In this context, restocking is an approach to solve an environmental problem (overexploitation on natural resources), either real or perceived (Cowx, 1998).

Manipulation of fish stocks by means of the addition of individuals or populations from outside the natural habitat is an old practice (Welcomme, 1998). In fact early aquaculture practices relied strongly on the transfer of material from the natural environment. With the development and diversification of various techniques of artificial breeding in the 1950´s and 1960´s, the aquaculture sector reduced its dependence on natural sources and at the same time offered an alternative source of seed for restocking plans of several species.

Initial practices of aquatic enhancement were mainly to support recreational fisheries; recent applications include the support of commercial fisheries and extensive aquaculture (Welcomme, 1998). Despite being commonly defined as the addition of animals to the stock as the means of enhancement, in the aquaculture context, various stock enhancement activities can be differentiated (Table 1.2).

Table 1.2: Definitions, descriptions and examples of existing enhancement methods.

Group	Description	Examples

I		
"Ranching"	Identifiable stock release with the intention of being harvested by releasing agency. Implies cost-benefit analysis based on comparing the harvested value with production, release and harvesting costs.	North Temperate Salmonids (Salmo, Salvelinus, Onchoryncus), sturgeons (Welcomme, 1996), Japanese marine ranching of Red Sea bream, flat fish, yellowtail and Karuma praw (Bartley, 1995)
II		
"Compensation"	Typically stocking with native species to compensate for a disturbance to the environment caused by human activities; e.g.: loss of habitat, lack of spawning substrate, etc.	Salmon stocks in the west coast rivers USA (Isaksson, 1988), and sturgeons stocks in Caspian Sea (Pavlov &Vilenkin, 1989)
III		
"Restocking"	Compensation for depletion of a natural resource. It is carried out after a limiting factor to stock recovery or improvement has been removed or reduced- water quality, habitat restoration, the easing passage for migratory fish or management of fishing pressure.	Corogenoid fisheries of the Nordic Alpine Lakes (EIFAC, 1994b), lobster species in the USA, France, England, Taiwan (Bartley, 1995; Bannister and Howard, 1991; Brand et al., 1991; Latroutie & Lorec, 1991; Liao 1997), scallops species in England, Taiwan (Latroutie & Lorec, 1991; Liao, 1997), clam, oyster and mussel species in Taiwan, England, USA (Liao, 1997; Brand et al., 1991; Bartley, 1995).
IV		
"Introductions"	Genuine addition of new stock in a river, lake or reservoir, which has not previously held that specie. It includes introduction of new species into existing fisheries to improve fish yield or fill a niche vacant.	Nile perch into Lake Victoria (Okewa & Olgari, 1994), stocking artificial reefs (Bannister, 1991), tilapia and carp species in Latin America (Welcomme, 1998), etc.

In general terms, any programme of enhancement is primarily applicable to the following kinds of aquatic species (Isaksson, 1988):

- Migratory species, usually anadromous that can be captured and harvested at or near the place of release (e.g. Salmonids).
- Stationary or sedentary species, that inhabit the oceans bottom, or live attached to artificial structures (e.g. Molluscs).
- Marine species, where recruitment of juveniles is limiting production of harvestable stocks (e.g.: Echinoderms).

World figures of geographical distribution of enhancement programmes into marine and freshwater reservoirs are based on very incomplete data (Welcomme, 1996; 1998). The following table illustrates a very wide guide of the number of countries, which lists a number of enhancement programmes reported to FAO.

Table 1.3: Figures of enhancement programmes reported to FAO (Welcomme, 1998).

	Freshwater and diadromous		Marine		
Region	**Fish**	**Crustacean**	**Fish**	**Crustacean**	**Molluscs**
Africa	26	2	7	5	2
Asia	16	4	5	8	2
Europe	18	3	8	3	3
Former URSS	5	-	1	-	1
North America	14	9	6	9	7
Oceania	6	5	1	4	4
South America	9	-	3	3	1
Total	**94**	**23**	**31**	**32**	**20**

These figures are very limited considering that they exclude countries such as China, Japan, India and Bangladesh, each of which reports enhancement stocking of several billion fry (Welcomme, 1998). For example, Japan reported a total of 5.8 million finfish, 5 million mollusc seeds, and 30 million crustacean larvae, released up to 1996 (Liao, 1997). These programmes included: 35 finfish species, 14 crustacean species, 27 mollusc species and 8 other species such as octopus, sea urchin and sea cumber (Liao, 1997).

Guidelines and stocking strategies are available in many countries. Despite most of them are species-specific and related to particular types of reservoirs; general issues and options to be taken can be applied to any specie. These strategies have been summarized by Cowx (1998). However, any restocking programme is subject to 4 conditions, to be met in order to success (Larkin, 1991):

- Ability to produce or even to collect fry or seed of good quality and quantity.
- Sufficient knowledge of recruitment mechanisms, in terms of correct times, locations and conditions to release and obtain successful recruitment.
- Capacity to recapture enhanced stocks.
- Adequate use rights to protect investments.

Before any restocking programme is implemented, a thorough evaluation of the reasons for the action must be done, and alternative enhancement approaches should be attempted, e.g. habitat improvement, fisheries management plans, etc. In this point, the use of community-based management strategies (Ahmed *et al.*, 1997) should be considered, in conjunction with proper informed extension activities and monitoring (Cowx, 1998).

Evaluation of restocking programmes should be only made in terms of the objective (Bannister, 1991; Cowx, 1998). According to Cowx (1994) the potential for a successful outcome is often limited because the specific objectives of the programme in relation to perceived problems and available resources are not fully appraised from the onset. Cowx (1998) affirms that any restocking plan should consider wide sectoral objectives, not just fishery objectives. Therefore, the evaluation of the restocking programme should be in terms of conservation and protection of the ecosystem, positive return and food security and/or employment.

A common lack of economic considerations in the design and evaluation of restocking is probably the reason for insufficient return rates in most cases. Restocking in many freshwater reservoirs is demonstrably cost-effective (Welcomme, 1998). The situation of marine systems is less clear and reported information suggests too low levels of cost-effectiveness to warrant these techniques as a major tool of management (Welcomme, 1996; 1998; Cowx, 1998).

1.6 Management of coastal resources in Chile: the system of Areas of Management and Exploitation of Benthic Resources (AMEBR)

Historically, all coastal fisheries in Chile have been subject to similar patters of exploitation and management plans. After open-access policies from the early 1940's to late 1970's, during the 1980's, management plans for these resources were based on traditional fishery regulations, e.g. temporary or permanent closed areas and global quotas or total allowable catch (TAC) (Gonzalez, 1996). During the early 1990's, management plans were characterized by the extension of the national closures, the allocation of global and individual quotas and long-term moratoriums for some species (e.g. 3-year moratorium for the Chilean abalone *Concholepas concholepas*).

As a result, the state of either full exploitation or overexploitation of the principal benthic fisheries in their traditional harvest areas forced the Chilean government to create and impose strict control measures. More recently, the exploitation and management of small-scale fisheries was institutionalised in the 1991 Chilean Fishing and Aquaculture Law (CFAL), which legalized the use of community-owned shellfish grounds, denominated "Areas of Management and Exploitation of Benthic Resources" (AMEBR).

AMEBR consider a strip of the territorial waters, from the low tide line to 5 miles offshore, stretching from the northern border of Chile to the 41° 28.6’ S parallel, as well as on inland and interior waters (GFAL, 1991). According to the regulations for AMEBR (Servicio Nacional de Pesca, 1996), these areas may be allocated only to artisanal fishing communities for a two-year period, upon the submission and approval of a management and exploitation plan (MEP) for one or more benthic resources. After this period (two years), these areas can be extended to an aquaculture lease, allowing further and controlled exploitation. This system was aimed at the achievement of sustainable exploitation of multiple species through the allocation of user-rights to established fishing associations. It also aims to improve productivity of benthic communities with the objective of maximising the socio-economic net benefits generated from its exploitation (Montecinos, 2000).

An AMEBR request must include a proposal for a Base Line Study (BLS) of the AMEBR specific situation and a resulting Management and Exploitation Plan (MEP), also defined as summary of norms and set of actions for the management of the fishery, based upon knowledge of related biological, technological, economic, and social aspects.

Since its establishment, the system of AMEBR has increasingly developed (Fig. 1.7), having received 349 requests for areas along the country, of which 184 have been approved, 122 are in process, and 43 have been rejected (Subsecretaria de Pesca, 2000b). With a total area of 43,202 Ha, approved AMEBR represent 62% of the total area requested. Nonetheless, this represents only 1% of the potential inhabitable area for target resources in Chile (Montesinos, 2000). Alongside, there are already 59 AMEBR currently implementing a MEP, mostly concentrated at the IV, V and VII Regions, signifying a project dealing with 5,000 organised fishermen (15% of the total number of registered fishermen) (Subsecretaria de Pesca, 2000b).

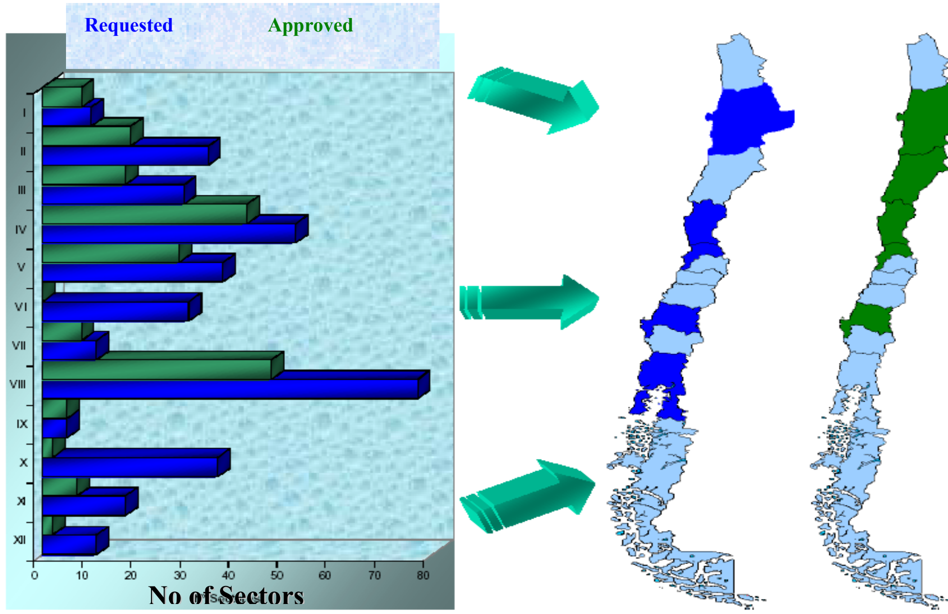


Figure 1.7: State of requested versus approved AMEBR sectors per Region in Chile, distinguishing the regions with higher number on each condition (Extracted from Subsecretaria de Pesca (2000b)).

Despite the newness of the implementation of the AMEBR in Chile, some specific cases can illustrate positive results for this management approach to solve one of the major problems in fisheries- overexploitation. For example, in Caleta El Quisco (V Region) 6 inshore benthic species have been managed since 1991- “Loco” *Concholepas concholepas*, sea urchin *Loxechinus albus*, stone crab *Homalapsis plana*, and 3 species of *Fisurella* spp. Comparison of mean size and catch per unit of effort (CPUE) between the El Quisco AMEBR and open- access fishing grounds, showed on one hand the effect of fishing on some benthic species, and the recovery of natural stocks on the other. All species, except stone crab, were larger in the AMEBR than in open-access areas outside the AMEBR (Castilla and Pino, 1996; Castilla and Fernandez, 1998).

Likewise, Oliva and Garrido (1994) reported positive results of management and exploitation plans undertaken in the coves of Las Conchas, San Pedro, Pichidangui and Totoralillo. In 1992, the fishermen organizations of these communities closed their management areas and the Instituto de Fomento Pesquero (IFOP) took daily statistics of landings from historical fishery grounds and management areas. Final results illustrated that mean sizes were significant smaller in historical areas as compared to management areas. In AMEBR of these locations, the mean yield was 25 Kg/h while in historical area was only 3 Kg/h.

More recently, the application of experimental management plans in Caleta Quintay (V Region) since 1994 has already shown optimistic results for keyhole limpet and sea urchin stocks. In this context, it has been observed an increase of, larger size classes of individuals and abundance of stocks in the AMEBR. Subsequently, the catch per unit of effort has diminished, and important unit- price improvements can be clearly observed between this site and historic fishing areas (Vega and Figueroa, 1998).

In general, as a result of increasing resource abundance inside the AMEBR, authorised capture volumes have also improved, which added to development on the commercialisation process has produced significant increases and stabilisation of landed prices for benthic products (Fig. 1.8) (Subsecretaria de Pesca, 2000b).

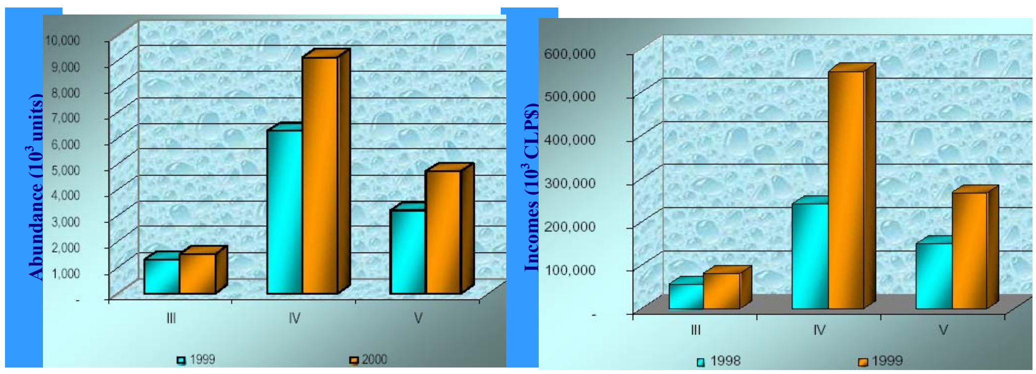


Figure 1.8: Resource abundance and incomes evolution for 'loco'-abalone managed inside the AMEBR operating at the III, IV and V Regions during 1998, 1999 and 2000 (extracted from Subsecretaria de Pesca (2000b)).

The AMEBRs may offer one of the best approaches to achieve sustainable fishing of inshore benthic resources Chile (Castilla and Fernandez, 1998). This is fully subject to adequate consideration of the various factors related to the use and/or preservation of resources. Consequently, various authors have suggested that management decisions for promoting the sustainable use of fishing resources in Chile should be based on investigations of the biological ecological, and environmental, as well as the technological, economic and social aspects (Gonzalez, 1996; Stotz and Gonzalez, 1997). Likewise, determinant factors and related issues and constraints must be considered in the establishment of the AMEBR though an ecosystemic, dynamic, and quantitative approach.

1.7 OBJECTIVES

Historically red sea urchin management has been based on traditional minimum capture size and closed season restrictions applied in an open-access fishery regime. Nowadays, together with the institution of the system of AMEBR, alternative management strategies to enhance productivity of the area are allowed and regulated. This includes: introduction of hatchery-reared juveniles (restocking), translocation and movement of individuals from and within the same coastal area, setting-up of seed-collectors and habitat improvements by generating artificial reefs or removal of specific species predators (Subsecretaria de Pesca, 2001). Along with this development, there has been an enormous technological progress in hatchery production systems, ensuring mass supply of restocking material, and a number of experimental and commercial restocking programmes in different locations in Chile have been successfully carried out, reporting encouraging results. Yet, there is no standard methodology, protocol or quantitative technique available to design, pre-evaluate and propose management plans for rational and sustainable management and exploitation of this important benthic resource, taking into account the multiplicity of factors and objectives interacting in this complex dynamic system.

Given this setting, the present work was aimed at developing and providing a user-friendly and flexible tool to design, pre-evaluate and analyse alternative and/or traditional management and exploitation plans for target species under the system of AMEBR. This was developed as a simulation model, specifically built to support decision-making on production design, quantitative analysis of biological effects on stocks dynamics, projection of socio-economic performance and profitability of the project, and spatial allocation and dynamics of coastal areas under management.

This research was also intended to analyse the wider management issues related to the regime of AMEBR, namely the projections for traditional management approach versus restocking-based enhancement activities. On this basis, restocking may be considered a major management strategy to recover natural stocks by supporting natural recruitment and allowing for sustainable commercial exploitation at historic levels, eventually solving the problem of overexploitation of the target species.

With the purpose of tackling these issues, the specific objectives of this research were defined as follows:

- To identify major fishery, biological, socio-economic and spatial causal factors and objectives influencing benthic coastal management, and develop a computer-based dynamic simulation model for flexible design, pre-evaluation and systems optimisation of traditional and alternative management plans of the Chilean red sea urchin within the framework of the system of AMEBR.

- To construct a systematic and logical procedure to determine the potential for restocking sea urchins within the subtidal and intertidal coastal zone, and develop a multicriteria GIS-based model to identify, quantify and select suitable sites to perform restocking exercises within delimited areas defined by a given AMEBR.
- To run and implement the simulation model on the basis of a real case study, and develop, optimise and propose a robust long-term management and exploitation strategic plan for the local sea urchin fishery at the AMEBR operating at the study area (Quintay, V Region, Chile).

1.8 METHODOLOGICAL FRAMEWORK FOR MODELLING

This research work comprised two major components, geographically separated and interrelated, during a 4-year period. The first, focused on the initial training and literature review at the beginning, and on data processing, modelling, analysis and writing up at the end, was carried out at the facilities of the Geographical Information Systems and Applied Physiology Laboratory (GISAP) at the Institute of Aquaculture, University of Stirling, Scotland. The second and intermediate stages were the fieldwork and data gathering, undertaken at the Cove of Quintay and nearby areas, based at the Marine Research Centre of Quintay (MRCQ), School of Aquaculture Engineering, University Andres Bello, Chile.

The following sections aim to describe the methodological framework used for laboratory-based and fieldwork activities during the development of this work. Detailed description of materials and methods used on each of the following stages are given in relevant sections of this thesis. Details regarding the protocols, specific questionnaires, outputs and data process relevant to the fieldwork stage are provided on Appendix 1 and 2.

1.8.1 MODELLING METHODOLOGY

In order to address the specific objectives of this study, the methodological framework was based on the application of *System Dynamics* (SD) and *Geographical Information Systems* (GIS) modelling.

Developed by Professor Jay W. Forrester at the Massachusetts Institute of Technology (MIT) in the late 1950's, SD has the main purpose of explicitly representing, combining and formalising conceptual models of reality. Through simulation models, it is possible to investigate the intimate relationships between model structure and behaviour of dynamic systems, design robust policies and strategies, and support tactical and operational decision-making applied to a wide variety of issues and problems (Davidsen, 1999).

A GIS is an integrated assembly of computer hardware, software, geographic data and personnel designed to acquire, store, manipulate, retrieve, analyse, display and report all forms of geographically referenced information geared towards a particular set of purposes (Borough, 1986; Kapetsky and Travaglia, 1995). GIS modelling is based on the integration of multiple factors for goal-oriented and hierarchical structured analysis of spatial data, to support natural resource assessment; management and decision-making on a wide range of applications, including aquaculture and fishery management (Ross, 2000).

Given the general modelling approach, the specific methodological framework for modelling the fishery system consisted of three sequential stages:

- Bio-socio-economic dynamic modelling
- Objective-orientated spatial modelling
- Model running and implementation

As the modelling process developed, major outputs and inputs were linked through specific data-flows and feedback processes organised, and systematised to form the final integrated model. The stages, major components, data-flows and feedback processes, major analyses carried out and final outputs, are illustrated in the following diagram (Fig. 1.9).

Bio-socio-economic dynamic modelling (I)

The aim of the stage I was to generate a dynamic and interactive simulation model, which allows resource managers to analyse the biological effects and economic outputs of different management strategies, specifically applied to a red sea urchin fishery operating under the system of AMEBR. This was achieved using SD modelling and a model-maker platform (Powersim Constructor® 2.51) to support structural construction, equation deduction, and computer implementation of the conceptual model developed. Model development involved four separate but closely linked modelling phases:

- Biological modelling of populations.
- Production modelling of system targets.
- Socio-economic modelling of the project.
- Spatial modelling of restocked coastal areas.

The final outcome of this process was the bio-socio-economic simulation model (BSESM), which described the stocks components dynamics, the design and projection of commercial and production targets of the system, the socio-economic requirements and financial evaluation of the project, and the spatial dynamics of potential restocking sites within the management area.

Objective-orientated spatial modelling (II)

The stage II was explicitly orientated towards the identification, quantification, and selection of potential sites for restocking hatchery-reared sea urchin juveniles, which were classified according to their suitability and area availability within the study area (AMEBRQ). This was achieved using multicriteria analysis, GIS modelling, and a supporting software (IDRISI32). The process involved the selection of determinant criteria influencing restocking activities, which were built based on hierarchical structures; the inclusion of decision makers' preferences (weights), which were combined through different arithmetic and weighted mathematical operations and routines, and the use of decision rules to produce the final output. The following stages were developed at the GIS-based modelling phase:

- Spatial modelling of the specific requirements of the specie.
- Spatial modelling of the operational factors associated with restocking.
- Spatial modelling of the available area for restocking.

The final output of the geographical information systems restocking model (GISRM) was a CROSSTAB-classification map showing all possible combinations of suitability and area availability for restocking in the study area. From this, the ten best (higher) suitability ¦ availability sites were chosen, and their estimated area was directly imported as input data into the BSESM during stage III.

Model running and implementation (III)

Once both, the BSESM and the GISRM were created, reviewed and systematized, the aim of the final stage was to test and run, implement and evaluate the application of the BSESM within a real system/data-based framework. The first part of this stage was achieved using SD optimisation and risk-management techniques (Saleh and Mytveit, 2000), plus a supporting software (Powersim Solver® 2.0), which provided with tools for tuning, optimising and analysing models. The second part and last point was carried out through field-based protocol with relevant fishery agents at the study area. Accordingly, the model running and implementation stage involved:

- Dynamic and static testing of the model's underlying theories, structure and operation.
- Design of macro-scenarios and deterministic case study-based run of the BSESM.
- Sensitivity analysis of critical assumptions of the model.
- Risk management, trade-off analysis and strategic management planning.
- Putting in practice, appraising and projecting the practical application of the BSESM.

The final output of the first part were two alternative strategic plans for long-term management of the red sea urchin fishery at the AMEBRQ, representing the best policy to be implemented so as to achieve the system targets, taking into account the potential variability of major risks.

The outputs of final stage allowed involving local fishermen and fishery managers into the modelling process and model implementation, and estimate its effective usefulness and project the future wider implementation of the BSESM in the actual fishery system of AMEBR.

1.8.2 FIELDWORK METHODOLOGY

The fieldwork stage of this research was undertaken during three separate phases, which considered different timing, objectives, planning and outcomes. These phases covered a period of approximately one year and three months, distributed amongst the first, second and third year of this research.

First fieldwork stage

For the duration of 6 months, the objective of this stage was to gain basic insights of the fishery system under study and gather necessary descriptive information and qualitative data to support the modelling process. Accordingly, this fieldwork covered the following aspects:

- Specific literature review and collection of relevant publications from a number of sources and agents.
- Analysis of technical and productive processes, including artisanal fishing activities, hatchery production system, coastal management plans, restocking programmes and resource monitoring programmes applied in the area.
- Collection of primary data on local and national scale regarding fishery statistics, cartography and resource-specific information.

- Preliminary gathering of bio-economic and socio-economic data related to productive processes previously analysed.

Second fieldwork stage

Having developed the first revised version of the simulation model and the conceptual structure of the GIS-based model, during 3 months this fieldwork had the purpose of gathering and providing all necessary input data to run these models. For this, semi-structured questionnaires, personal interviews, discussion groups, post and Email communications were designed and used with a variety of agents, including fishermen, fishery managers, aquaculture and marine biology related scientists and researchers from private and governmental institutions. In global terms, this fieldwork comprised the next elements:

- General socio-economic characterization of the fishing community.
- Localised assessment of socio-economic needs and expectations from the fishery.
- Direct and active participation in resource assessment, planning and design of management and restocking programmes for target resource at the AMEBRQ.
- Collection and analysis of resource population assessment data, and species-specific parameters and biological-productive indexes.
- Quantitative assessment and collection of economic data relevant to capital and operational costs, incomes and profitability indices of major productive processes.
- Analysis of local markets, products, prices and commercialisation processes.
- Collection of GIS-based model specific input data.

Third fieldwork stage

The aim of the final fieldwork was to apply and evaluate the usefulness, in order to project the future application of the BSESM within the artisanal fishing sub sector. This was achieved through a number discussion groups, interviews, tutorials and various presentations with the local fishing association representatives, technical support unit members, and staff of the Marine Research Centre of Quintay, at which the BSESM was instructed, implemented and tested. This fieldwork covered the following issues:

- Diagnosis of decision support tools needs in the sub sector.
- Assessment of technical capabilities, hardware and software within the fishing association.
- Determination of the understanding and acceptation degree by fishery agents.

- Operational assessment of application of the BSESM, and projection of wide future use in the system of AMEBR.

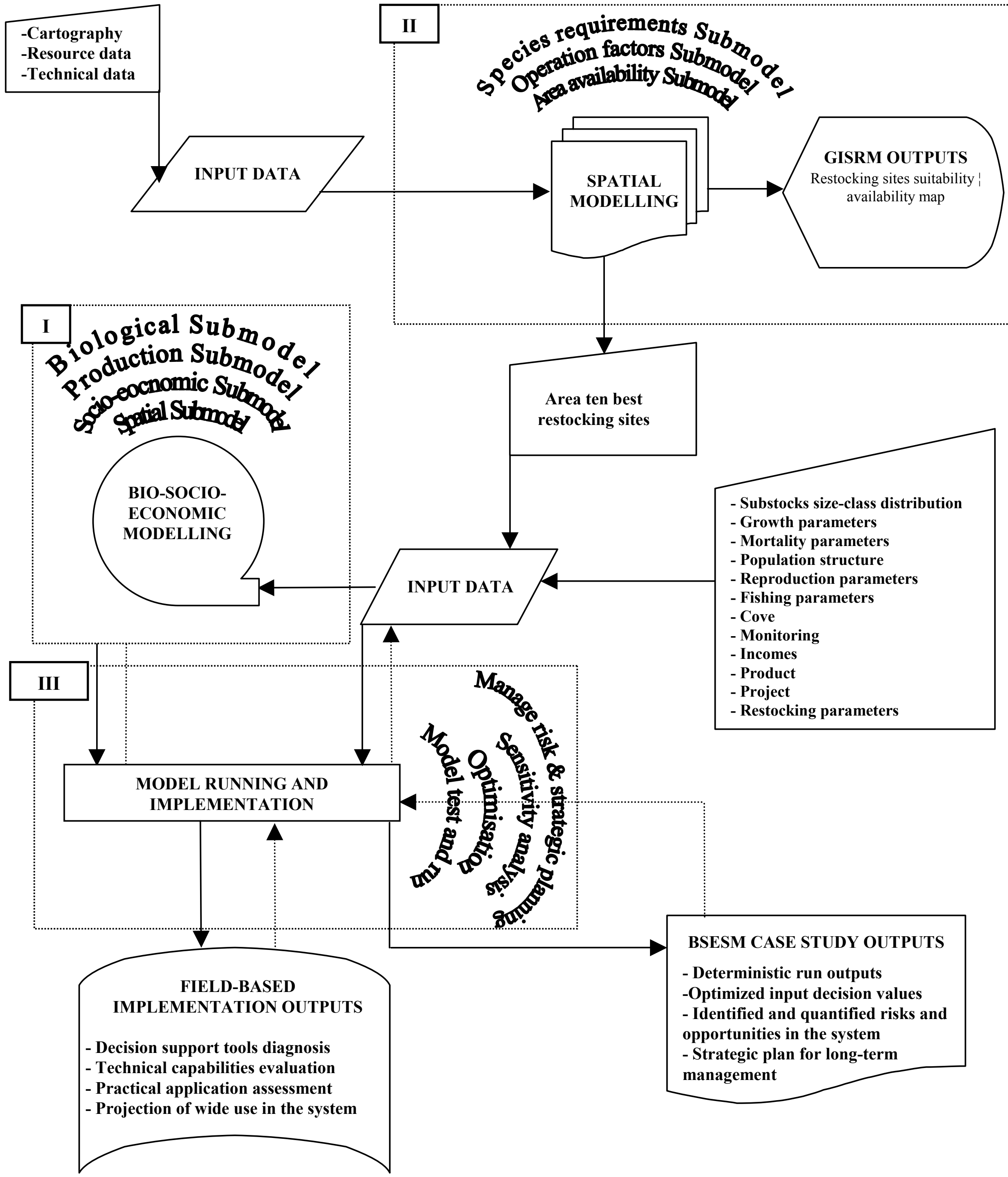


Figure 1.9: Methodological framework used for modelling the system.

CHAPTER 2

THE STUDY AREA AND MANAGEMENT PROGRAMME

2.1 GEOGRAPHICAL LOCATION AND DESCRIPTION

The cove of Quintay ('Caleta' Quintay) is located in the central coast of Chile (33º22`S, 72º42`W), only 18 Km South of the port city of Valparaiso, V Region (Fig. 2.1) and about 110 Km from the capital, Santiago. Of a total population of 650 (Instituto Nacional de Estadisticas, 1992), approximately 100 rely on small- scale fisheries as their major livelihood (Ossa, 1997). Including their families, this group constitutes 90% of the local population; therefore artisanal fishing is the principal economic activity of the zone.

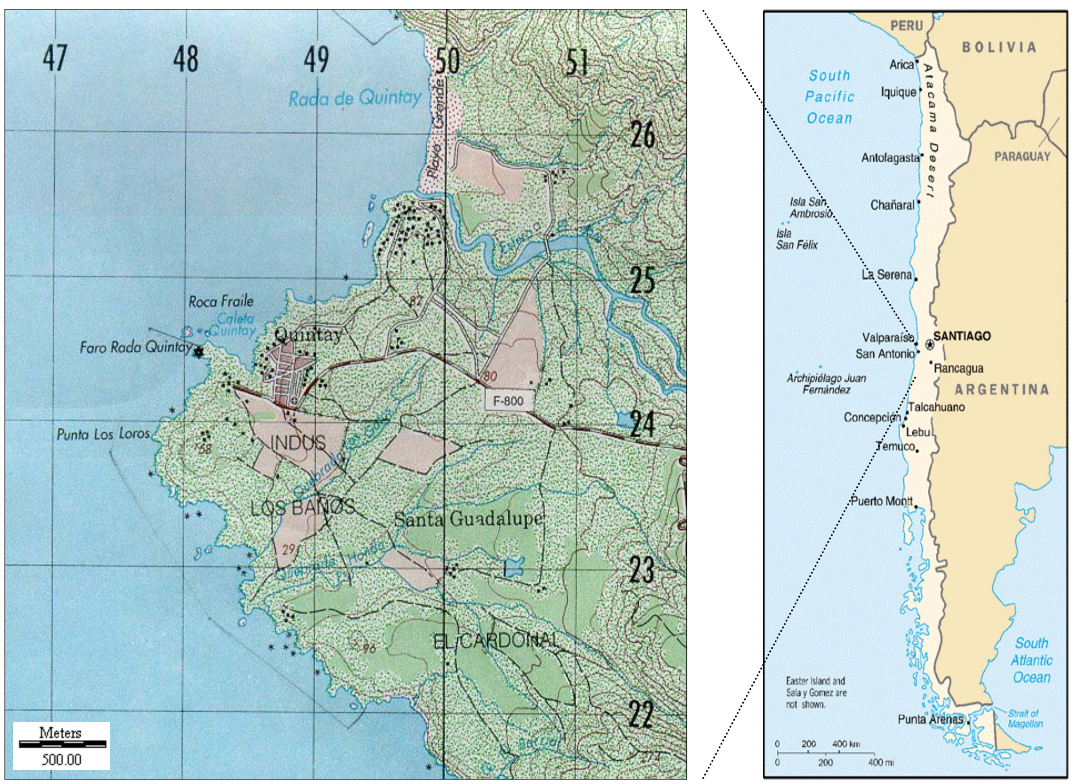


Figure 2.1: Geographic location of the cove of Quintay.

'Caleta' Quintay has been described as a typical rural, geographically isolated Chilean cove (Fig. 2.2). A key characteristic is its very delimited fishing ground where benthic shellfish resources constitute an important contribution to local economy (Oliva and Castilla, 1990a). By comparison other economic activities, such as local tourism and commerce are relatively unimportant (Castilla, 1989).

Figure 2.2: The cove of Quintay.

Early development of the zone was through the establishment of a whaling plant (‘Planta Ballenera de Quintay’), which operated from 1940 to 1967 (Fig. 2.3). Captured whales were brought in vessels to Quintay, butchered, boiled and processed in a huge infrastructure specially built for this purpose along the southern wing of the bay (Fig 2.4). Products were then sent out by sea (fuel oil and pet food) (Heebner, 2000).

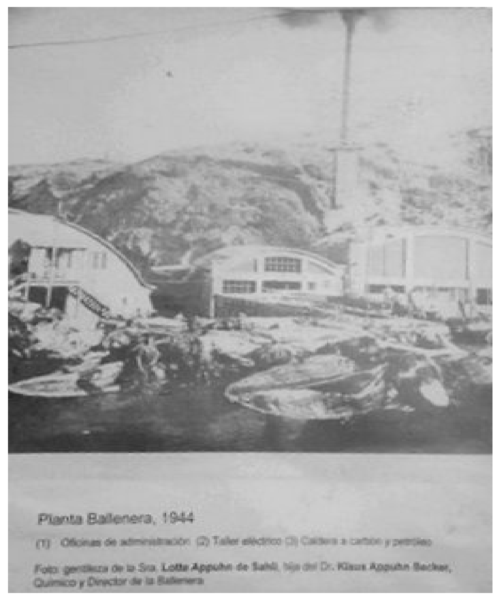


Figure 2.3: ‘Planta Ballenera’ Quintay.

Beginning in the early 1950’s, settlements started developing along coastal areas around Quintay, focused on recreation and tourism activities (Ossa, 1997). More recently, complexes of vacation homes have begun to crowd the area. The largest of these investments (Resort Santa Augusta) was planned to accommodate up to 8,000 people (Fig. 2.4). Despite high expectations for the commercial success of this project, low revenues to date have limited further development stage.

Despite the settlement of the resort close to the fishing community, it was helpful in solving some environmental problems in the area, but also generated others. The project provided some alternative employment for the local population, and communications and road infrastructure also improved. On the other hand, access to clean drinking water became limited. This was a point of contention between the community and the tourist facility, which took a year to be resolved (Ossa, 1997). In addition to this development, smaller tourism activities are restricted to typical seafood restaurants, scuba- diving clubs and recreational fishing on the main beach.

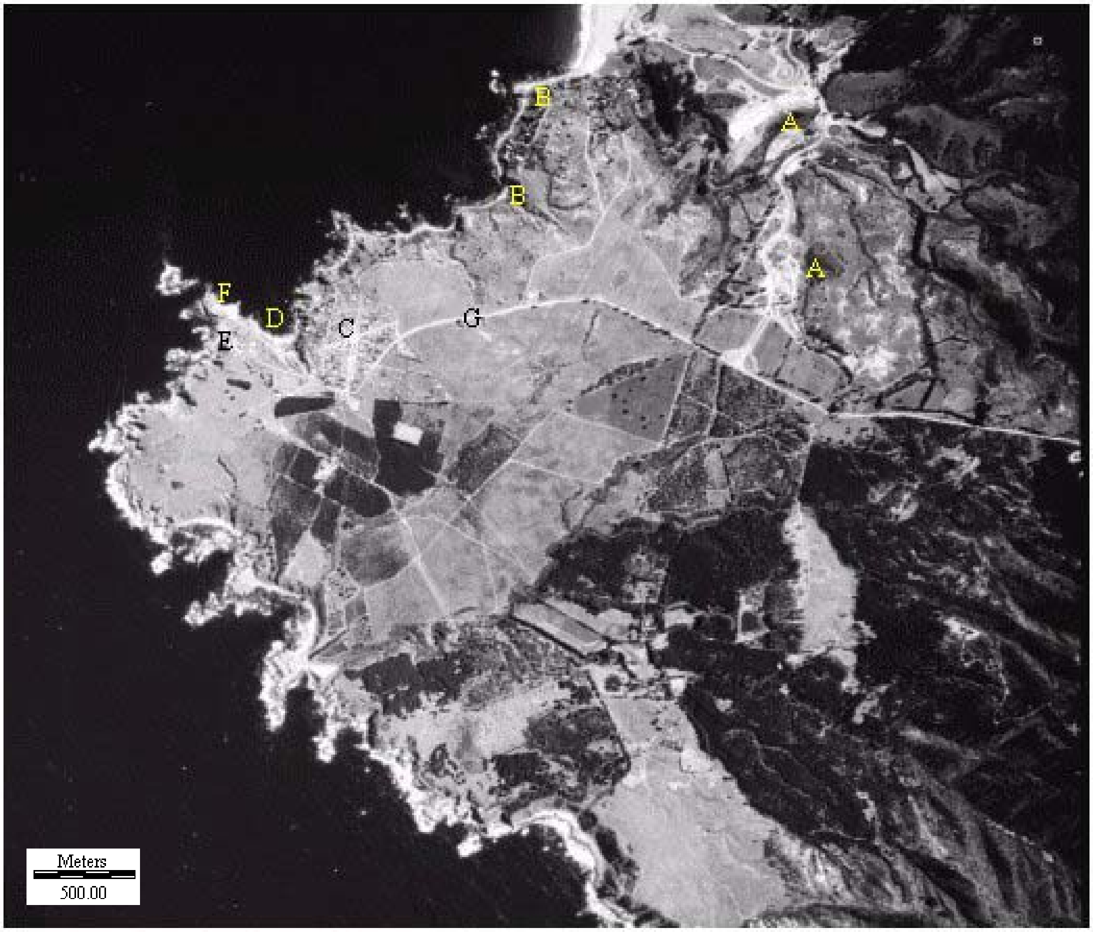


Figure 2.4: Aerial photograph of the region (Servicio Aereo Fotogtametrico, 1994).

A: Resort Santa Augusta	**E:** Marine Research Centre of Quintay
B: Other vacation settlements	**F:** Old whaling station
C: Quintay village	**G:** Main road access
D: Quintay bay and cove	

2.2 ARTISANAL FISHING ACTIVITIES

In the cove of Quintay, fishing activities have been historically performed along the coastline delimited between Punta Curaumilla in the North (33°05’40’’S, 71°44’18’’W) and Caleta Tunquen in the South (33°15’43’’S, 71°39’55’’W) (Fig. 2.5). This fishing ground has been mostly exploited and geographically dominated by Quintay’ s fishermen for many years (Castilla, 1989).

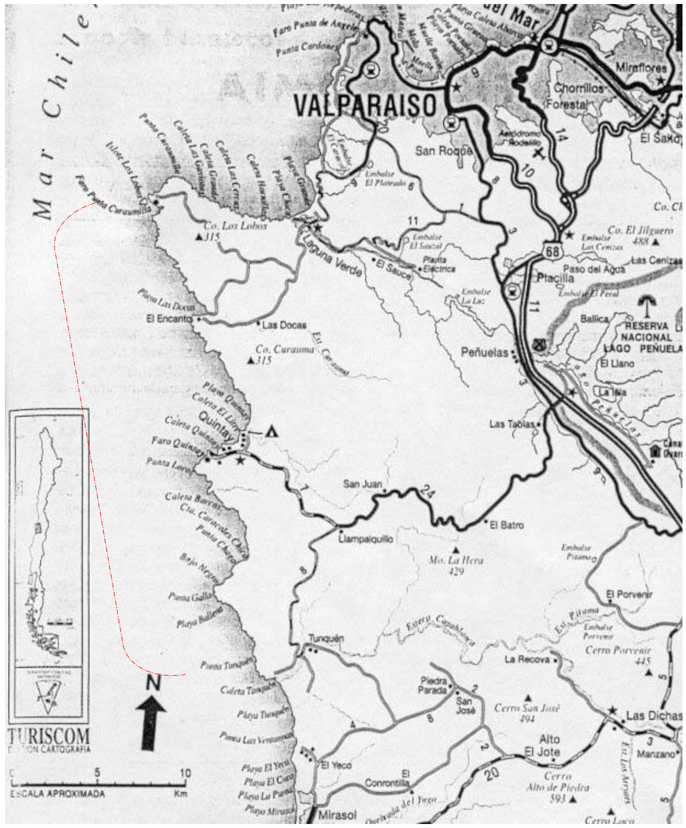


Figure 2.5: Historical fishing ground of Quintay's fishermen.

The coastline is very exposed to wind and swell (Fig. 2.6), and so climatic and oceanographic conditions strongly regulate artisanal fishing activities, and restrict its practice to a few limited sessions during the open season, which varies with the species.

Figure 2.6: Characteristic wave-exposed coastline.

Fisheries of this area include pelagic finfish, benthic molluscs and echinoderms. Among the first group, 'congrio colorado' *Genypterus chilensis*; 'congrio negro' *Genypterus maculates* and 'sierra' *Thyrsites atun* and 'tiburon' *Isurus oxyrinchus* are the major target species. The second and possibly more important group in value is formed by gastropod molluscs such as 'lapa' *Fissurella* sp. and the muricid 'loco' *Concholepas concholepas.* The last group is constituted by the Chilean red sea urchin *Loxechinus albus,* the only echinoderm caught by small- scale fishing activities in the area (Figueroa et al., 1998). Among these, *Loxechinus albus, Concholepas concholepas*, and *Fissurella maxima*, are the principal species in terms of relative abundance of natural stocks and biological and fishery knowledge, but more importantly because of their commercial value and revenues in local, national and international markets (Figueroa *et al.*, 1998b).

In practice, extractive fishing on these benthic resources is carried out by hookah and also free diving on intertidal and subtidal zones at depths ranging between 3 and 25 m (Fig. 2.7). Generally, this is based on a team of four people, the skipper, a crewmember, and two divers. Here, the skipper is in charge of navigating the boat and the crewmember is responsible for controlling the compressor and assisting the two divers during the fishing session.

Figure 2.7: Scuba- diver extracting sea urchins.

The fishing fleet at 'Caleta' Quintay currently accounts for more than 30 open- boats ('bongos') ranging between 3 and 7 m hull- length, equipped with outboard motors, air compressors and complete diving equipment (Fig. 2.8). In general the boat, out- board motor, air compressor and fishing gears are family- owned, but diving equipment usually belongs to individuals (Association of Independent Artisanal Fishermen of Quintay, pers. comm. 2000). The size of the local fishing fleet has been variable, increasing during some periods and decreasing in others. Likewise, the number of skippers, crew and divers making up the local fishermen's association has fluctuated throughout the last two decades (Castilla, 1989; Asociacion de Pescadores Artesanales Independientes de Quintay, pers. comm., 1999).

Figure 2.8: Artisanal fishing boat and diving air-compressor equipment.

2.3 THE RED SEA URCHIN FISHERY

The red sea urchin *Loxechinus albus* is an extremely important resource in the local benthic fishery (Asociacion de Pescadores Artesanales Independientes de Quintay, pers. comm., 1999). Incomes generated from commercialisation of this echinoderm have historically been equal to those obtained from key- hole limpets (*Fissurella* spp.), whose total volume for the three species concerned is larger. This amount is approximately half the income generated from 'loco'-abalone fishery in the zone (del Campo and Perez, 1999).

The zone's sea urchin fishery is not only relevant locally, but also regionally. The Quintay fishing grounds have been traditionally very significant within the central zone of Chile, at between 20 and 25 % of total sea urchin landings of Region V (Servicio Nacional de Pesca, 1990).

The fishing period for this species in Quintay extends for 9 months, as defined by the legal closure, from 15 October to 15 January (Subsecretaria de Pesca, 1999). During this period, effective fishing is carried out for 5 to 28 days at a time in different zones within the fishing ground, depending on the climate and oceanographic conditions (Asociacion de Pescadores Artesanales Independientes de Quintay, pers. comm., 2001).

The capture is sold directly by the fishermen to intermediaries and wholesalers at a price that currently varies between [1]CLP$ 200 and $ 300 per urchin (Registro official, Asociacion de Pescadores Artesanales Independientes de Quintay, unpublished data). The product is sold at the beach unprocessed and then transported in refrigerated container trucks to processing plants in Valparaiso, San Antonio and Santiago.

The unit price depends on the final market for the product, which is based on size. Sea urchins sized between 7 and 8 cm diameter without spines are directed to higher priced international markets. While, bigger individuals sized between 8 and 12 cm are mainly destined for national and/or local markets (Fig. 2.9). Size selection criteria are based on the quality of the gonad, such as texture, colour and consistency, which is supposedly more uniform and better in smaller individuals (Perez pers. comm., 2000).

Figure 2.9: 10- cm test diameter commercial individual.

As with most commercial benthic resources in Chile, the red sea urchin was strongly overexploited during the 1980's and 1990's. Most of the major and easily-accessible stocks in the central coast were almost depleted (Fig. 2.10).

Figure 2.10: Red sea urchin bed.

[1] £1=CLP$900-1,000

This was also the case for Quintay, where landing figures during the last decade in (Fig. 2.11), clearly showed the critical state of over- exploitation.

For the period of 1990 to 1993, registered landings increased continuously reaching a maximum of 47 t. Based on a fairly constant effort, ranging between 19 and 23 boats, this increase was a result of very strong and increasing fishing pressure over stocks returning high levels of catch per unit of effort (Table 2.1). Thereafter, from 1994 to 1998 catch per unit of effort decreased severely, describing a highly diminished population levels unable to support commercial exploitation any longer.

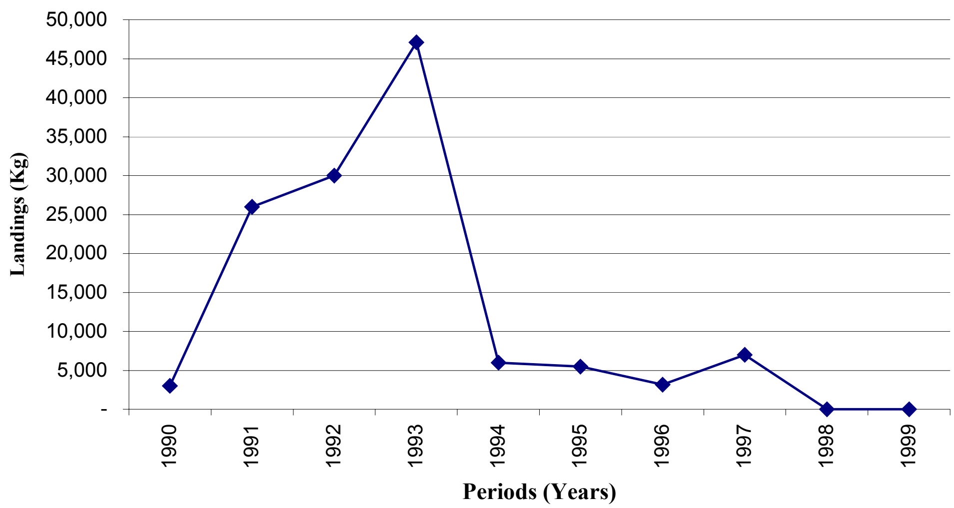


Figure 2.11: Registered landings of the red sea urchin *Loxechinus albus* at the Cove of Quintay (Registro official, Asociacion de Pescadores Artesanales Independientes de Quintay, unpublished data)

Table 2.1: Landings, fishing effort and commercialisation data registered at the cove of Quintay from 1990 to 2000 (Asociacion de Pescadores Artesanales Independientes de Quintay, unpublished data).

Year	Units (5- 6 urchins/Kg)	Fishing fleet (boats)	Total catch per unit of effort (units/boat)	Unit Price (CLP$/unit)	Size Range (mm)	Final market
1990	16,500	19	868	50	70- 80	Exportation Industry-
1991	143,000	20	6,810	50	70- 80	Exportation Industry
1992	165,000	21	8,250	60	70- 80	Exportation Industry
1993	259,050	23	11,263	70	70- 80	Exportation Industry
1994	33,000	25	1,320	80	80- 120	Local- national
1995	30,250	23	1,315	120	80- 120	Local- national
1996	17,419	19	917	150	80- 120	Local- national
1997	38,500	19	2,026	180	80- 120	Local- national
1998	-	19	-	200	80- 120	Local- national
1999	-	19	-	250	80- 120	Local- national
2000	-	19	-	300	80-120	Local- national

As a consequence, the Quintay fishermen themselves were forced to establish a total closure on fishing for this resource. The closure of the fishery was aimed at building-up the harvestable stock in the fishery, as a way to ensure higher prospective population levels. This measure has been applied and respected for more than three years in some of the most traditionally productive areas of their fishing ground, as it is the sector B of the AMEBRQ that is described below.

During the 1990s, the average unit price increased continuously reaching a maximum of CLP$250 in 1998. Furthermore, the larger volumes exported during the 1991- 1993 period resulted in the near depletion of individuals of the 7- 8 cm size- class. This was caused by high international markets prices for this product, which still predominate. Average sizes of more recent landings (8-12 cm) clearly support this situation. The need to supply the market then resulted in the exploitation of the remaining commercial stock available in the zone (Table 2.1).

From 1998 to date, the red sea urchin is captured outside the management area leased to the Association. These areas are ruled under non- ownership rights, where only general fishing regulations such as the closure season and minimum legal size for the resource are applied. Is clear that although the conservation management plans implemented by the local fishermen's Association have stabilised this deleterious pattern, these have been restricted to a limited area only, and further effective actions will be necessary more widely.

2.4 THE LOCAL MANAGEMENT AND USE OF BENTHIC RESOURCES BY ARTISANAL FISHERMEN

The artisanal fishermen of Quintay are formally and legally aggregated into the 'Asociacion de Pescadores Artesanales Independientes de Quintay' (APAIQ). This entity was created in 1985 and since then the organisation and all its members are registered in the Artisanal Fisheries Registry and the National Service of Fisheries. There are currently 72 active members of the APAIQ, covering a variety of fishing positions and a range of ages. The education level section of the socio-economic survey (for details refer to Appendix 2) revealed an average secondary school level of education among the members aged between 25 and 65 years old. Even before its formal creation, this group was widely recognised as being highly organised and innovative decision- makers, far ahead in terms of administrative management of its own structure and of the natural resources on which it relies. This resulted in several research projects and coastal leases being assigned to this organisation.

In 1969, a designation of 5,255 m^2 inland and 3,935 $m^2$of seabed was approved allowing the use of the beach as a dragging platform, construction of net and fishing gear- hanging systems, storage boxes, and rooms for trading and sale of the products. In 1991 an area of 521,000 m^2 (Fig. 2.12) of fishing ground and water body was legally assigned for development of a research project focused on a natural repopulation programme and management plan of the 'loco'- abalone *Concholepas concholepas*. The programme involved direct and active participation of the fishermen and was supported by the research group 'Estacion Costera de Investigaciones Marinas' (ECIM), belonging to 'Universidad Catolica de Chile' (Castilla, 1988).

Figure 2.12: General view Sector A 'Caleta' Quintay.

More recently, under a relatively new fisheries scheme, this organisation was assigned a 'Management and Exploitation Area of Benthic Resources' identified as Sector B Quintay (Fig. 2.13, Table 2.2). The area is described as the 'Area of Management and Exploitation of Benthic Resources of Quintay (AMEBRQ)', and the coastal lease covers 104 ha of seabed and water body, and allows the organisation the use and management of specific benthic resources in this area. These are 'loco'- abalone, three keyhole limpet species and the Chilean red sea urchin *Loxechinus albus*.

Since then, various evaluation studies, management programmes and exploitation plans have been undertaken. A series of evaluations have been carried out on 'loco'- abalone, which have assisted in calculating total abundance and biomass of this important resource. This essential data has been used in decision-making and to establish permissible capture volumes throughout the years. These evaluations have also trained fishermen in sampling methodologies, and more importantly have developed increasing interest for conservation and management issues among the local community. The technology for natural repopulation developed for *C. concholepas* in Quintay established a model for other coves and generated important baseline data for the implementation of the system of Management and Exploitation Areas in Chile (del Campo *et al.*, 1999).

On a similar basis, management plans for the rational exploitation of *Fissurella*. spp. have been developed within the AMEBRQ. In recent years, high variability and decreasing trends of the stocks of 'loco'- abalone in the area, generated increasing interest in the three species of this group. At the present this resource constitutes one of the major benthic resources for artisanal fishermen, as important as *C. concholepas*, due to growing commercial interest and increasing prices of the product in national and export markets (del Campo *et al.*, 1999).

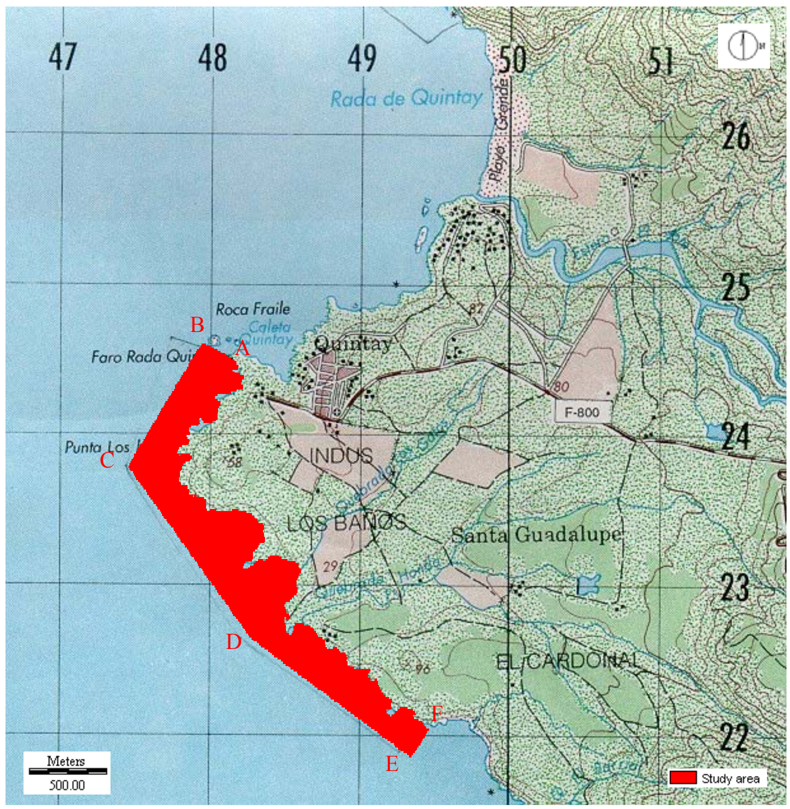


Figure 2.13: Geographic location of the Area of Management and Exploitation of Benthic Resources of Quintay (AMEBRQ).

Table 2.2: Geographical position coordinates of the AMEBRQ.

Vertex	Latitude S	Longitude W
A	33° 11' 18.91''	72° 42' 6.10''
B	33° 11' 14.67''	72° 42' 14.60''
C	33° 11' 40.70''	72° 42' 34.30''
D	33° 11' 18.10''	72° 42' 4.20''
E	33° 11' 44.50''	72° 42' 24.30
F	33° 11' 38.15''	72° 42' 19.20''

For the red sea urchin, commercial exploitation inside the AMEBRQ was totally suspended in 1997. As previously mentioned, this management measure was entirely self-imposed and was widely respected by local fishermen. Subsequently, and based upon the results obtained from a Base Line Study in 1999, a massive restocking programme and management plan was approved and initiated in 2000. A brief description of the Base Line Study methodology, results and analysis, and the management project designed for the red sea urchin inside the AMEBRQ, presented by the AIFAQ and approved by the Under Secretary of Fisheries and Aquaculture, is given in following sections of this Chapter.

2.5 THE MARINE RESEARCH CENTRE OF QUINTAY

Belonging to the National University Andres Bello, the 'Centro de Investigaciones Marinas de Quintay' (CIMARQ) (Figure 2.14) was founded in 1990 in order to support applied research and undergraduate academic activities in Aquaculture, Fisheries, Environmental Science and Marine Biology. The centre is located in the old whaling station area, opposite the northern end of the AMEBRQ, on the South of the Bay (see Fig. 2.4).

Since its creation and because of the location and mutual interests this centre has maintained a close link with the APAIQ, initiated in 1993. This relationship has allowed the development of several activities, which after 7 years of interaction have resulted in a framework of mutual co-operation, training and technology transfer.

The CIMARQ has supported and supervised all the practical operations, evaluation studies and technical surveys, and produced formal requests and resource management and exploitation plans presented by the APAIQ before the Under Secretaries of Fisheries and Aquaculture, acting as the official Technical Unit for all projects. Among the latest projects, the Base Line Study, and subsequent Management and Exploitation Plan developed for the five benthic stocks previously mentioned, were entirely planned and executed, and are still being supervised and monitored by the research staff at the centre.

Since 1993, within the major technological research projects, a series of practical studies were carried out at the CIMARQ focused on developing different stages of large-scale hatchery production for red sea urchin juveniles. This project was initially supported through a National Technological Fund (FONTEC), which proposed this resource as an efficient natural bio- fouling controller for intensive longline culture of scallops with a mixed culture system. During this stage, 500,000 juveniles sized between 5 and 10 cm diameter were produced at the centre (Vega and Figueroa, 1998).

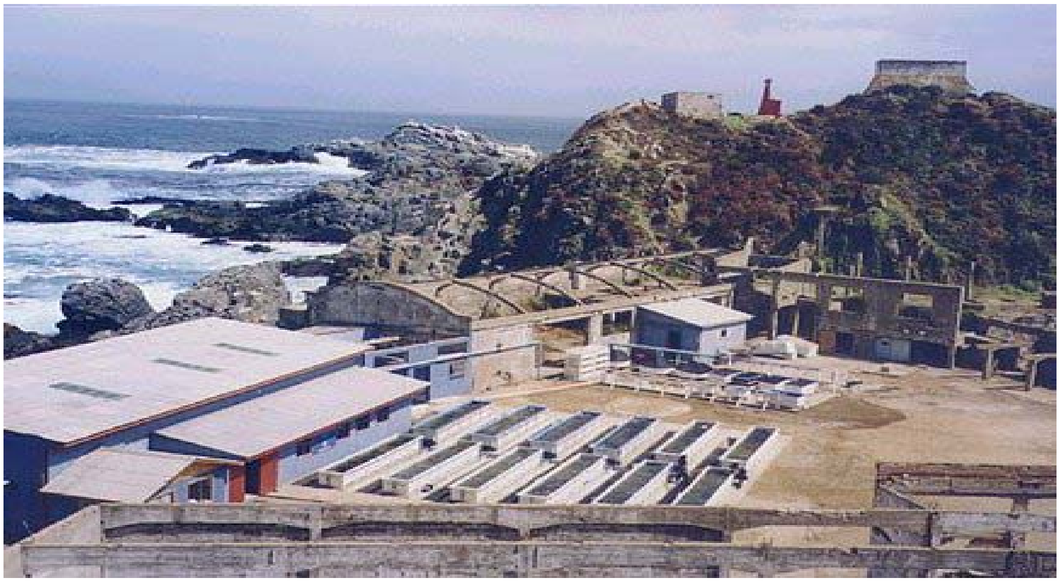


Figure 2.14: General overview of the 'Centro de Investigaciones Marinas de Quintay' (CIMARQ). (Note raceway- based system for settlement and culture of sea urchin juveniles).

To date large- scale hatchery production of red sea urchin juveniles has been successfully completed. With the current infrastructure (Table 2.3) of the CIMARQ, the total production capacity under normal conditions is approximately 1 million juveniles/year, (Figueroa. pers. comm., 1999).

Table 2.3: Current culture infrastructure and capacity of the CIMARQ for production of red sea urchin juveniles.

Stage of production cycle	**Culture facilities**	**Installed capacity**
Larval culture	Larval culture room	6 (500 L) conic tanks (Fig. 2.16) 6 (1,000 L) conic tanks
Natural food production	Microalgae culture room	800 L mass culture/ week (Fig. 2.17)
Settlement and juveniles culture	Outdoor culture raceways	12 (3,000 L) raceways (Fig. 2.18) 30 (20 settlement plaques) sets each

The production cycle starts with the collection and induced spawning of mature adults (Fig. 2.15), which are generally obtained from nearby areas. These are collected one or two days before the induction process, which is a KCl dose injection by the aboral orifice. Once spawned, eggs are fertilised and moved to aquaria for series of washes.

Figure 2.15: Red sea urchin adult individuals.

Fertilized eggs are then maintained in the aquaria until a majority of them reach the 'prism larvae' stage. At that point, they are redistributed into conical tanks (500-1000L), where the larval culture stage takes place for a period of two months using filtered water (Fig. 2.16).

Figure 2.16: Conical tanks for larval culture.

Here the larvae is feed on microalgae (*Chaetoceros gracilis* and *Chaetoceros calcitrans*) on a daily basis and cultured at an average density of 2 to 3 larvae/ml (Fig. 2.17).

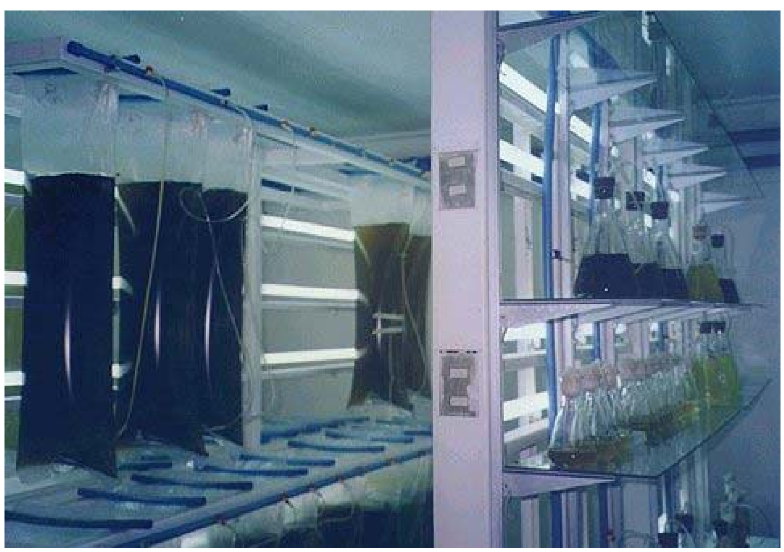


Figure 2.17: Microalgae culture room.

Once the larvae are ready for metamorphosis, they are moved into outdoor raceway systems, containing sets of fibreglass layers (Fig. 2.18). This substratum has been previously conditioned for two to four weeks, allowing the formation of thin layer of diatoms that effectively induces the settlement of the larvae and provides a natural food resource for early juveniles.

The culture of juvenile takes place in the same raceways with a constant flow and permanent aeration. During this stage (8 to 10 months), the stock feeds on nutrients in the water flow and also on macroalgae artificially supplied on a weekly basis. The process results in juvenile sized between 2 and 3- cm diameter (Fig. 2.19).

Figure 2.18: Raceway-based system for sea urchin juvenile culture in Quintay.

Alongside the development of this aquaculture production system, CIMARQ staff have carried out activities focused on the experimental stocking of hatchery- produced sea urchin juveniles into the AMERB assigned to the APAIQ. These aimed to generate the necessary information to undertake a long- term mass-restocking plan, potentially allowing sustainable exploitation of this resource in the zone. The following aspects were developed in the course of the first experimental restocking project in Quintay (Figueroa, 2000):

- Mass hatchery production of sea urchin *Loxechinus albus* juveniles
- Selection of fast- growing individuals for restocking.
- Site selection for restocking.
- Release of 16,000 two- cm diameter juveniles.
- Evaluation of growth and survival rates of released individuals.
- Evaluation of the economic potential of the restocking plan for fishing community.

Final results obtained after two years of research allowed practical selection criteria to be developed and suitable areas for restocking to be identified. The average survival rate registered after 27 months of evaluation was 35.90 %. Furthermore, monthly growth of 1.6 ± 2.8 mm was significantly better than that previously reported for the species in repopulation studies in Chile (Figueroa, 2000).

Figure 2.19: Red sea urchin juveniles produced at the MRCQ.

2.6 Physical and resource characteristics in the AMEBRQ

2.6.1 Base Line Study

The General Law of Fisheries and Aquaculture, promulgated in 1991, included a new administrative instrument, the so- called Regimen of Areas of Management and Exploitation of Benthic Resources (AMEBR). This regulation had the major objective of conceding territorial rights for exclusive use of coastal areas by artisanal fishermen organisations, in order to practice the management and exploitation of benthic resources (Norambuena and San Martin, 1999).

Within this scheme, the Under Secretary of Fisheries and Aquaculture established a general protocol, which regulates the procedure, and covers three sequential stages:

- Official request of the Area of Management and Exploitation of Benthic Resources
- Development of the Base Line Study (BLS)
- Development of the Management and Exploitation Plan for the area (MEP)

The aim of the BLS is to establish the physical characteristics of the management area and the state of the benthic resources on it, prior to the implementation of a MEP for the major commercial resources. The methodological proposal for the development of the BLS must cover the following technical specifications (Table 2.4).

Currently, the State of Chile is prepared to promote, disseminate and co- finance the development of the BLS and the preliminary stage of the MEP (Norambuena and San Martin, 1999). This has been realised through public funds specifically assigned for this purpose, which partially support the costs of the BLS.

Table 2.4: Major aspects to be considered in the BLS (Sevicio Nacional de Pesca, 1996).

General features of the area
Identification of requested area indicating its geographic co-ordinates.
Identification of major species indicating common and scientific name(s).
Information regarding previous studies carried out in the area, including copy of the reports, papers, etc.
List of relevant secondary species at the area.
Objectives of the BLS
Description of local benthic community, with special attention to species of commercial and ecological importance.
Direct determination of the principal species.
Identification, characterisation and distribution of existing types of substrata and its bathymetry.
Sampling methodology
Minimum sampling unit.
Minimum sampling area.
Sampling design according to the characteristics of the area and the specie.
Description of sampling methods used.
Working plan
Activities.
Periods.
Expected results

The following sections aim to describe the general methodology, major results obtained, analysis and interpretation and during the development of the BLS in the context of the project AMEBRQ for the red sea urchin fishery. This project was carried out by the CIMARQ and APAIQ during 1999. Data collection, processing and final report of the BLS were developed by the CIMARQ staff. Data analysis and development of the MEP component specifically proposed for this species was carried out during the first fieldwork phase of this Thesis. The scale (1:2000), resolution (1 m), and the way in which each target resource was separately evaluated and analysed, resulted in a data set which is uniquely detailed. Furthermore, given the innovations in the design and development of the plan, this contributed significantly to the establishment of a standardised evaluation methodology for benthic resources in Chile.

2.6.2 MAJOR, SECONDARY AND OTHER COMMERCIAL SPECIES IN THE STUDY AREA

Major (commercially targeted) species for management and exploitation were selected according to their economic importance and current state of over- exploitation in the zone. Secondary species were selected on the basis of their association to the principal species previously identified (Table 2.5). An additional group of species was also identified based on their potential for management and controlled exploitation within the study area (Table 2.6).

Table 2.5: Major and associated secondary benthic species present in the AMEBRQ.

Secondary species– predator →	Principal species →	Secondary species- prey
Meyenaster gelatinosus	*Concholepas concholepas* “Loco-abalone”	*Cirripedis*
Heliaster heliantus		*Mussels*
		Tegula atra
		Tegula tridernata
Lutra felina		*Crutocean algae*
Mugiloides chilensis	*Loxechinus albus* “Erizo rojo”	*Mazaella*
Graus nigra		*Chondrus*
		Gelidium
		Ulva
		Chondrus
	Fisurella maxima “Lapa castellana”	*Crutocean algae*
		Gelidium
		Ulva
		Chondrus
	Fisurella cumingi “Lapa negra”	*Crutocean algae*
		Gelidium
		Ulva
		Chondrus
	Fissurella latimarginata “Lapa frutilla”	*Crutocean algae*
		Gelidium
		Ulva

Table 2.6: Other species present in the AMEBRQ.

Molluscs	Crustaceans	Finfish	Algae
Chiton spp.	*Rinchocinetes typus*	*Paralichtys microps*	*Durvillaea antarctica*
Tegula atra		*Paralichtys adspersus*	*Gelidium rex*
Ostrea chilensis		*Semicossyphus maculatus*	*Porphyra chilensis*
Argopecten purpuratus		*Aplodactylus punctatus*	*Lessonia nigrescens*
Aulacomya ater		*Genypterus maculatus*	*Lessonia trabercualata*
Venus antiqua		*Genypterus chilensis*	
Nucela calca		*Prolatilus jugularis*	
Fissurella crassa		*Sicyaces sanguineus*	
Fissurella pulcra			
Xanthochorus crassiformis			

2.6.3 BATHYMETRIC AND SEABED TYPE CHART

The thematic map, of bathymetric profiles and seabed types, was dimensioned according to the stratification regulations suggested on the Technical Document AMEBRQ N° 1 (Subsecretaria de Pesca, 1997).

Taking into account the area of the coastal zone involved (≈104 Ha), the final scale was 1:2000. Original maps were drawn in AutoCAD 14, and printed in three separated sections of the study area. An independent group specially commissioned for the BLS carried out the cartographic sampling and mapping. The following figures (Fig. 2.20 and 2.21) are IDRISI 32 raster files derived from a series of operations including importation, digitalisation, and interpolation routines, using the original vector files (for details refer to Chapter 4).

The study area has a large rock- type seabed intercepted with sandbanks (Fig. 2.22), and a maximum depth of about 49- m. Seabed composition can be classified into three main groups (Table 2.7).

Table 2.7: Bottom type composition in the AMEBRQ.

Sea bed type	Area (Ha)	Coverage (%)
Volcanic rock	31.17	30.01
Ball- type rock	69.73	67.14
Sand	2.94	2.85
Total	**103.84**	**100.00**

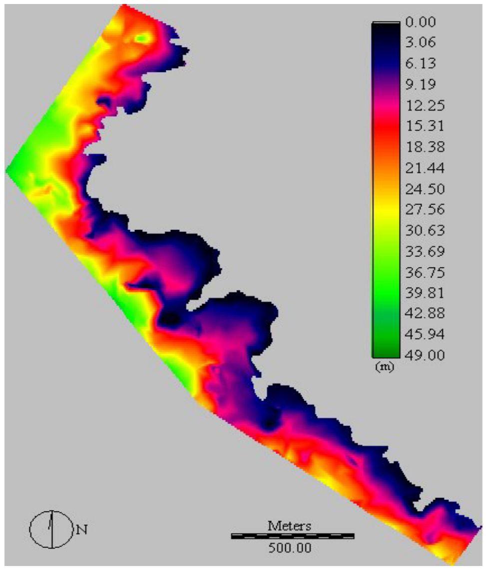


Figure 2.20: Bathymetric chart of the AMEBRQ**.**

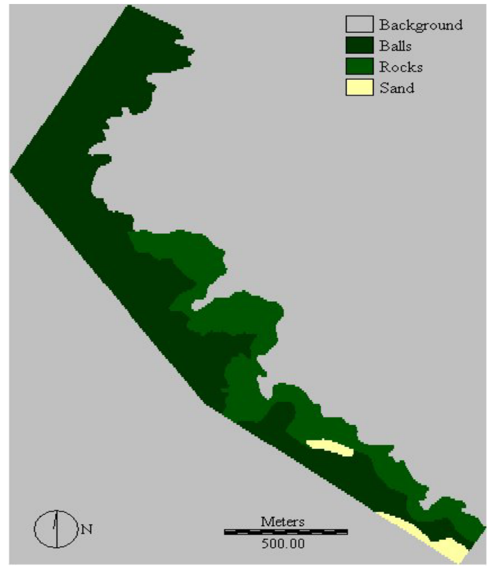


Figure 2.21: Seabed type chart of the AMEBRQ.

Figure 2.22: Characteristic intertidal and subtidal rocky seabed of the sector.

2.6.4 THE BENTHIC CHART AND STATE OF RED SEA URCHIN STOCKS

Methodology: field-based sampling and analysis of the sample

The stock evaluation covered the major settlement areas, which were previously identified and localised by means of specifically located surveys during a pilot sampling, but also based on historic and up to date information provided by the local fishermen.

The pilot sampling consisted of the selection of specific coastal areas within 10 m depth, considering both: coastline zones and offshore reefs. Here, a number of boats and trained divers worked on the identification, localization and size estimation of the major sea urchin sub-stocks in the AMEBRQ, and hence the potential distribution area for this resource.

The potential inhabitable area of this species was calculated assuming a continuous surface, limited by the perimeter area extended from the densest patches to the lower density- zones. Those potential areas are described in detail on the benthic chart (Fig. 2.27). In this zone sea urchins distribute in a contagious pattern forming patches, and it constitutes the major habitat for this species.

Following the pilot sampling, the final stock assessment involved the participation of 7 boats, which were distributed among the potential distribution areas previously identified. Each boat sampled 3 transects, at which five 1m^2 quadrants were randomly selected within the potential distribution area (Fig. 2.23).

Divers were trained to delimit the specific sub- zone where the sample was taken, and localization of transects was determined by means of a GPS navigation tool, and described by the particular characteristics of sampled sectors.

The total number of individuals on each quadrant was counted and extracted. Mean density and effective coverage (estimation of the area covered at the time of sampling) was determined for each target species, including a qualitative description of the community associated with them.

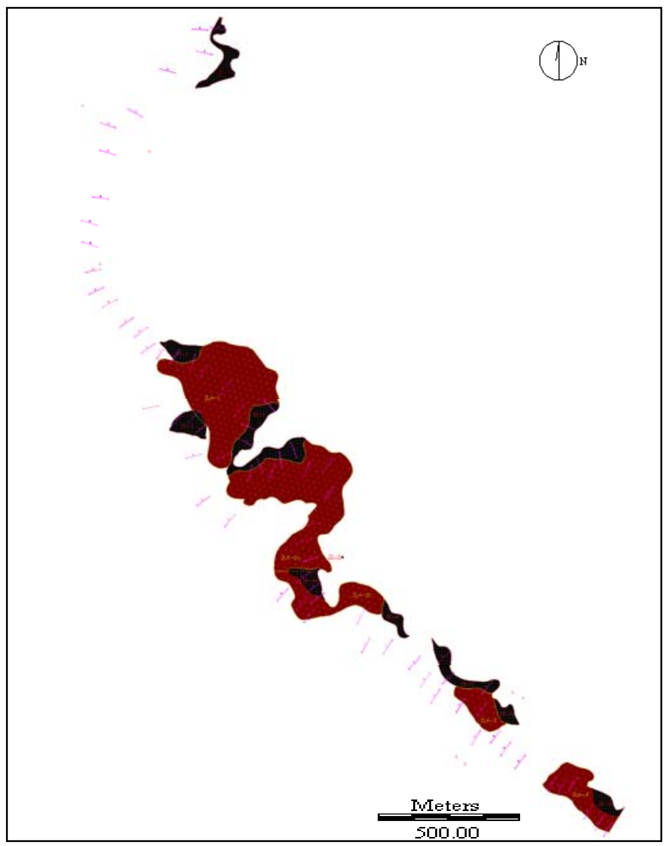


Figure 2.23: Location of sampling transects on sea urchin (black) and keyhole limpet (red) major sub-areas of abundance.

The sample was then transported to the MRCQ where it was stored in outdoor aerated tanks for measurement (diameter and height of the test) and weighing procedures. The animals were finally returned to the sea at the same zone of extraction.

The total number of individuals in each sub- stock sampled was estimated as follows:

$$\mathbf{TN = MD * EA} \quad \textbf{[individuals]} \qquad \textbf{[Equation 2.1]}$$

where: **TN:** Total number of individuals [units]; **MD:** Mean density [units/m^2]; **EA:** Effective area [m^2].

Individual length and weight were adjusted to a potential curve according to the function below:

$$W = a * L^b \quad \textbf{[g]} \qquad \textbf{[Equation 2.2]}$$

where: ***W*:** Individual weight [g]; ***a*:** Constant curve intercept; ***b*:** Curve slope.

Finally, the total biomass was estimated using the following equation:

$$\mathbf{TB = \Sigma_{i=0} (NT * \mathit{W})} \quad \text{[individuals]} \qquad \textbf{[Equation 2.3]}$$

where: **TB:** Total biomass of the population [g]; **W:** Individual's weight for *i* size frequency [g]; **NT:** Total number of individuals for *i* size frequency [units].

In order to determine the inhabitable area for the 'loco' resource, criteria based on seabed type were used, of which ball- type rock and rocky areas are the most suitable habitat. Similarly, the inhabitable area for keyhole limpet species (*Fissurella* sp.) was estimated using a mixed seabed and depth- based criteria.

Results

The spatial distribution of the principal species sub- stocks (geographic location and spatial coverage) was based on a 50 m point- resolution on the chart (Fig. 2.24). Areas so described correspond to higher abundance zones of resources of 'loco'- abalone and keyhole limpets, and major patches of red sea urchins.

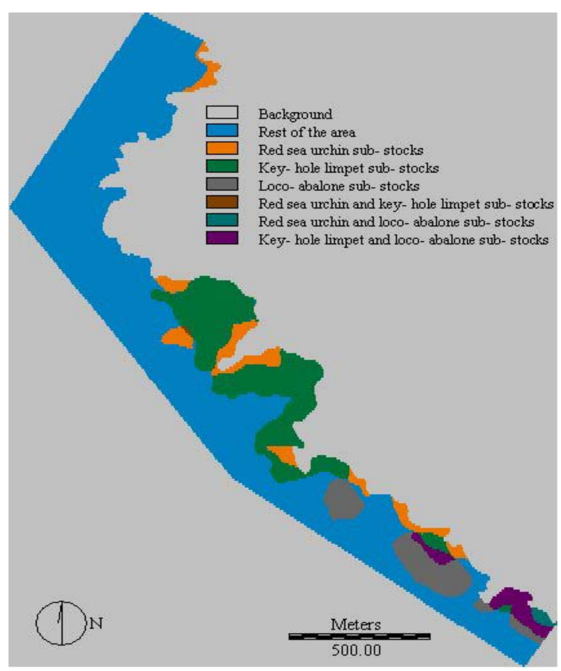


Figure 2.24: Benthic chart of the AMEBRQ.

The total estimated inhabitable area for the 'loco' resource was 1,009,210 m^2, which constitutes 97.15% of the AMEBRQ. Most of the abundance zones were associated with major banks of cirripedians, a characteristic feature of the area described. These food resources cover approximately 91,565 m^2 (8.81% of the AMEBRQ) in the study area.

For keyhole limpet species, rocky seabed zones between 5 and 20- m depth with highly abundant algae, were identified and characterised. The zones defined had a total area of 202,435 m^2 (19.49% of the AMEBRQ).

Regarding the red sea urchin, based on the pilot sampling procedure previously described, main distribution zones or patches were identified, describing a total inhabitable area of 65,265 m^2 (6.28% of the AMEBRQ).

The AMEBRQ has 9 major separately defined sub- stocks in irregularly shaped- patches, with an overall population estimated at 452,775 individuals (Fig. 2.24). Among these, 6 were sampled (Sub- stocks 1 to 5, and sub- stock 7). These were selected as the major sub- stocks, described by local fishermen.

Abundance results calculated per quadrant and patch area (effective coverage) are shown in Table 2.8. Sub- stock 7 showed the largest populated zone with 192,033 sea urchins.

Population density among the sampled transects was highly variable with an average of 27.8 individuals/m^2 and a standard deviation of 34.25 (Fig. 2.25).

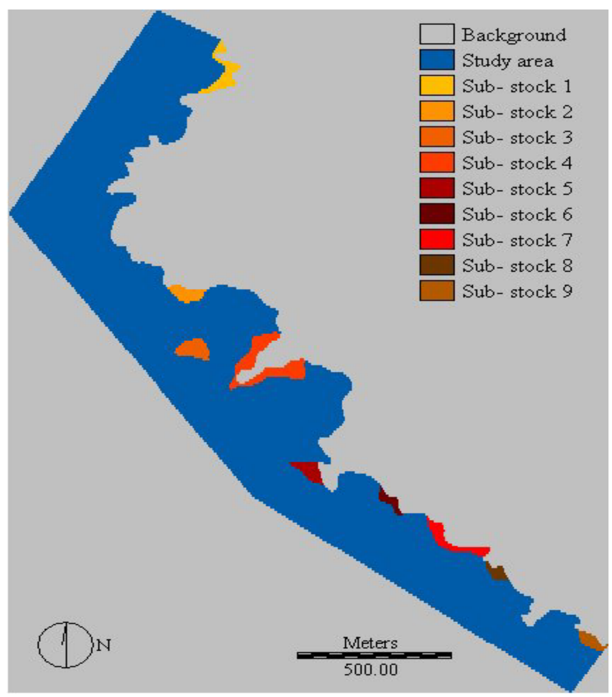


Figure 2.25: Geographic distribution of major red sea urchin sub- stocks in the AMEBRQ.

Fig. 2.26 shows the size frequency distribution for the resource. The major frequency was the 60- mm size- class among the population. Figure 2.26 illustrates the potential curve adjusted for the relation weight- test diameter for *Loxechinus albus* in the AMEBRQ.

Based on the size- class frequency distribution, the exploitable fraction of this resource (adults sized ≥ 70 mm) at that time was calculated at 221,552 individuals. The seed population (18- 32 mm) was estimated at 41,321 individuals and the intermediate juvenile population (32- 70 mm) was calculated at 180,231 individuals.

Table 2.8: Abundance of *Loxechinus albus* per patch area analysed in the AMEBRQ.

Transect	Quadrant	Substock 1	2	3	4	5	7
	1	70	60	32	176	8	120
	2	43	30	27	99	4	132
1	3	0	0	15	90	4	81
	4	0	0	1	24	3	20
	5	60	0	58	88	12	0
	1	45	42	20	70	4	0
	2	0	18	23	127	3	78
2	3	58	12	21	31	1	90
	4	0	0	23	20	2	34
	5	0	0	35	90	9	0
	1	53	23	60	29	9	0
	2	40	0	15	13	4	43
3	3	0	0	18	130	3	32
	4	0	0	8	0	3	46
	5	55	0	18	0	3	147
	Mean (individuals/m^2)	28.27	12.33	24.93	65.80	4.80	54.87
	Deviation (individuals/m^2)	28.27	18.86	16.21	53.89	3.14	50.40
	Patch area (m^2)	1840.00	3100.00	1450.00	3440	2070.00	3500.00
	Potential area (m^2)	8529.99	5634.75	7255	38222.28	5476.52	8492.16
	Patch population (individuals)	52010.7	38233.3	36153.3	124408.0	9936.0	192033.3
	Total population (individuals)	**452,775**					

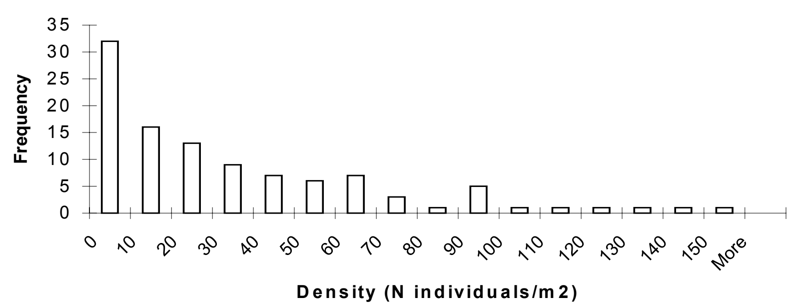


Figure 2.26: Density frequency histogram for *Loxechinus albus* in the AMEBRQ

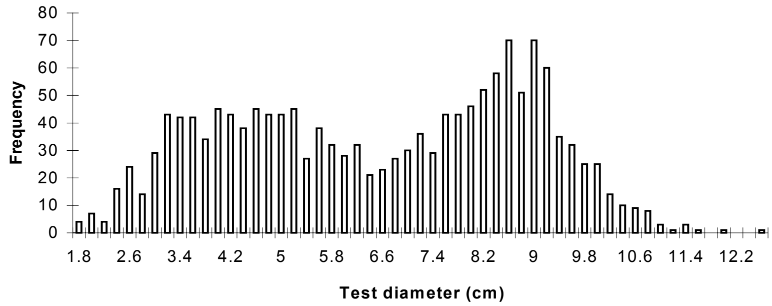


Figure 2.27: Size- class frequency for *Loxechinus albus* in the AMEBRQ.

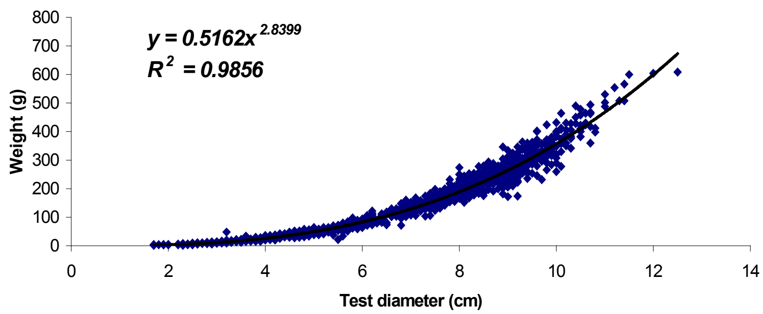


Figure 2.28: Relation test diameter- weight estimated for *Loxechinus albus* in the AMEBRQ

Analysis and interpretation

A large rocky coverage and high spatial heterogeneity characterizes the AMEBRQ. Both features allow sustaining high densities of target species- "loco" *C. concholepas*, "lapa" *Fissurella* sp., and red sea urchin *L. albus*. In fact, this coastal area has been historically very important in terms of its natural productivity and accessibility, and constituted the major fishing ground for the local fishermen community.

The AMEBRQ presents very suitable conditions for the establishment of management and exploitation plans for the target species. With only 2.85% of sandbank coverage, the rocky bottom constitutes the major seabed type (97.15% of total area). This is the optimum substrata for the gastropods "loco" and "lapa", and the red sea urchin, which occupies a variety of habitats in rocky zones along the Chilean coastline (Larrain 1975; Oliva and Garrido, 1994; Stotz and Perez, 1992).

Various studies on the bathymetric distribution and migration patterns associated to different life stages of these benthic resources have suggested the existence of differential optimum habitats for recruits and adults (Guisado and Castilla 1987; Castilla 1990, Moreno 1999). According to Moreno (1999) an ideal management area should present both types of habitats. In this context the spatial heterogeneity characteristics described for the AMEBRQ satisfactorily fulfil this condition.

Excepting for the red sea urchin, mean density values obtained for target resources showed normal distribution. This was due to a significant number of quadrates where no presence of sea urchins was detected during the sampling, resulting on a high variation coefficient.

This situation is mostly determined by the contagious distribution pattern of the specie, forming isolated aggregations or patches, which determines a very localized and delimited vertical distribution. Even though this difficulty was accounted in the sampling methodology by pre- defining the patch areas, the process was highly complex due to the seabed morphology, bathymetric profile and wave-exposure of the area. Hence, special consideration must be taken in future evaluations to define more precisely the geographic distribution of major stocks, which may be influenced by seasonal events such as reproductive cycles and/or food abundance and distribution.

Effective distribution substrata for the red sea urchin in the study area described a rocky seabed at depths ranging between 0 and 10m. This represented the smallest effective distribution area (65,265 m^2) among the benthic resources assessed. This relative spatial inefficiency would be directly determined by its vertical distribution pattern and substrata preference.

Despite this limitation, feeding habits and strategy of the red sea urchin (it feeds on non-specific drifting macro- algae particles) (Contreras and Castilla, 1987), would enable a given population to occupy most of the effective distribution area, regardless of the macro-algae coverage in the area. Studies carried on sea urchin natural stocks protected from human exploitation for 6 years in southern Chile, have proved that food is not a limiting factor for the development of a given population, which size may increase constantly (Lepez, 1988).

Size distribution illustrated a large harvestable stock (size classes$\geq$7 cm) in comparison to the other size classes, accounting for almost half (48.93%) of the population. The occurrence of such stock could be explained on the basis of combined contribution of three major sources:

- successful recruitment during 1991 to 1993,
- remaining juvenile size classes after 1994 to 1997, and
- stock build up process due to the recent closure of the fishery.

Considering normal natural growing rates estimated for this specie in the central coast of Chile, minimum commercial size is reached within 4 to 5 year growing period. Thus, at least small and medium sized individuals (7.0cm≤sizeclasses<9.0 cm) forming up the harvestable stock in 1999 could have been generated from successful recruitment during 1991 to 1993.

Despite is virtually impossible to determine the source of recruits, the size of brood stock in the area may be used as a good indicator of recruitment in that season. In this context, landings of red sea urchin in the Quintay Bay between 1991 and 1993 were characterized by increasing and high volumes, which reached a maximum of 259,000 units in 1993. The magnitude of these landings provides an approximated description of the size of the existent population in that time, but more importantly an estimate of the brood stock. According to this, could be established that during this period the total population of sea urchins in the Quintay Bay exceeded 259,000 individuals. Moreover, taking into account the mean size of captures registered (between 70 mm and 80 mm) and that sexual maturity occurs on individuals sizing between 38 mm and 47 mm (Castilla, 1990), could be inferred that the brood stock was considerable, and surely larger than 259,000 individuals.

The fishing pattern developed during 1991 to 1993 targeted sizes between 7.0 cm and 8.0 cm mainly destined for international markets. Describing high levels of exploitation registered, this probably resulted in a population structure dominated by juvenile and non-commercial sized adults, with minimum presence of commercial sized individuals (7.0cm≤sizeclasses≤ 8.0 cm) and minor representation of large individuals (sizeclasses>8.0 cm).

The critical situation reached on stocks by 1994 at Quintay Bay, forced the fishing community to target larger individuals remaining in the commercial fraction. Confirming this, the extractive pattern and landing volumes observed during the following years (1994-1997) were based on the exploitation of individuals sized between 8.0 and 12 cm at lower volumes for national market.

In a similar way to the one observed in the former period, natural stocks of larger commercial size classes were heavily over- harvested and practically depleted during 1994 to 1997. This could be demonstrated by the total absence of individuals larger that 12.6 cm in the samples taken from the AMEBRQ during the BLS in 1999. This fishing pattern has been previously described in other harvested populations of red sea urchins under open-access regime in Salinas (central coast of Chile) (Castilla 1990). Here, size distributions showed population structures truncated on the 5.0 to 6.0 cm- size classes and insignificant representation of commercial size classes. This is produced by a systematic and constant extraction of commercial size classes in traditional fishing grounds (Duran *et al.,* 1987).

Based on this analysis, would be possible to affirm that most of juveniles population remaining from the exploitation carried on 1991 to 1993 did not incorporate to the harvestable stock in 1994 to 1997. Therefore, an important proportion of this population contributed directly to the larger size classes (sizes≥9.0cm) in the estimated stock in 1999.

Lastly, is most probably that the large harvestable stock estimated in 1999 was simply a result of stock build up process due to the recent closure of the fishery.

The current population structure also shows very small representation (5.24 % and 3.24%) of the two major non- commercial adult classes (5.8 cm≤sizeclasses<7.0 cm) in relation to the ones integrating the commercial stock (23,738 and 14,653 individuals respectively). Poor recruitment levels that probably took place during 1994 to 1997 could explain this result. Then, major size classes of brood stock population, which were already significantly diminished, were progressively reduced and practically depleted.

The larger representation (between 10.55 % and 11.97% each) of the following three smaller size classes (3.4≤sizeclasses<5.8cm), could be determined by the major contribution of accumulated slow- growing recruits generated in 1997 and 1996, and minor recruitment supply during 1994 to 1997.

Finally, seed size class structure showed a decreasing representation in relation to size, with a maximum of 7.12 % for 2.6 cm to 3.2 cm size class and a minimum of 2.01 % for 1.8 cm to 2.4 cm size class. These results could be explained by the single or combined action of two major elements, as referred to:

- sampling errors that constrained the finding of smallest individuals hidden in cracks and holes in the rocks, and
- poor recruitment levels during 1998 to 1999.

The BLS results revealed a population that had been recently over-harvested, with limited but above all variable recruitment. This population also showed a certain recovery, mostly due to the recent closure of the fishery. However, improvement on recruitment levels is uncertain.

Abundance results revealed that natural stocks are recovering satisfactorily, but would not be able to support long- term commercial and sustainable exploitation.

In addition, based on the estimated mean density (27.28 individuals/m^2), the maximum carrying capacity of this area, as a function of the effective distribution area, would be 1,780,429 individuals. Contrasting this amount to the one obtained in this study (452,775 individuals) may reveal that sea urchin natural stocks in the AMEBRQ are largely under its maximum potential size.

2.7 CURRENT MANAGEMENT OF BENTHIC RESOURCES

2.7.1 THE MANAGEMENT AND EXPLOITATION PLAN

According to the regulations for AMEBR, these areas may be allocated only to artisanal fishing communities for a two- year period, upon the submission and approval of a Management and Exploitation Plan (MEP) for one or more benthic resources. After this period, the area can be extended to an Aquaculture lease, allowing further controlled exploitation. The AMEBR request must include a proposal for a Base Line Study (BLS) of the specific AMEBR and a resulting Management and Exploitation Plan (MEP) (Servicio Nacional de Pesca, 1996).

The MEP is defined as summary of norms and set of actions allowing the management of the fishery, based upon knowledge of biological, technological, economic, and social aspects related to the fishery (Servicio Nacional de Pesca, 1996).
In addition to this, the technical terms of reference for the official request of an AMEBR by artisanal fishermen's associations must consider the following specific aspects (Gonzalez, 1996):

- The requested area must be a part of available areas for the allocation of AMEBR, declared by the National Fisheries Service, Chilean Fisheries Undersecretary, Ministry of Economy of Chile. This area must not overlap, totally or partially, other areas previously established for Aquaculture or AMEBR's purposes.
- The zone must be the natural habitat of the main species targeted by the MEP.

- The MEP must consider resource and environmental conservation, and avoid any disturbance or negative impacts on the environment.
- The MEP cannot contemplate introductions of individuals from other areas than the AMEBR. Nevertheless, aquaculture produced- seed may be allowed; and in specific cases, a one- time introduction of outside individuals may also be permitted.
- The MEP does not allow the removal and/or reallocation of secondary species and individuals outside of the AMEBR.

Even though the requirements of the MEP are not specified in the regulations, there are a minimum number of issues, which must clearly be covered in the proposal (Gonzalez, 1996):

- General and specific objectives of the MEP.
- Methodological steps, based on the results of the BLS, indicating studies and activities to be conducted in order to support the MEP and productivity of targeted species.
- Annual exploitation plan of the area, specifying harvest periods, techniques, and production targets for each resource.
- Full description of all the activities and timetable for there.
- Expected results of the MEP within the short and medium term (2 to 5 years).

Within this context, after finishing the BLS at Quintay, in late 1999, a MEP was designed with 'loco'- abalone and for keyhole limpet as the targeted species. A separate plan was also specifically focused on the red sea urchin, in the form of an Integrated Coastal Management and Restocking Programme for the red sea urchin *L. albus*. These three components constituted the MEP presented to the National Fisheries Service during 2000. Although few guidelines for it application were suggested, the plan was accepted and approved.

Administration measures for the management and use of the target species were then applied immediately and are currently operating in the study area. The following sections provide a general description of the major management measures considered for the red sea urchin.

2.7.2 Restocking and Coastal Management Programme for the red sea urchin

Based on the results of the BLS, the aim of this programme was to achieve partial recovery of historical stocks and consequently a significant increase in harvestable biomass in the AMEBRQ. The methodological framework was based on the design of a mass-restocking programme in conjunction with a number of coastal management measures, in order to support natural recruitment in the area (del Campo and Perez, 1999).

The final programme was structured into three major components: a restocking programme, a coastal management and exploitation plan and an evaluation and monitoring study.

The restocking programme was dimensioned according to quantifiable productive targets during, at the end of and after the implementation. Hence, the number of seed to be released during the first year was estimated on the basis of a number of productive factors, limitations, and restrictions. The final productive target was agreed at a total population of 1 million sea urchins present in the area after a period of 4 to 5 years. This amount was calculated considering a minimum harvestable stock 300,000 individuals and projecting a minimum recapture and harvest of 120,000 individuals/year by the end of the programme. The target capture volume (120,000 individuals/year), was estimated from the minimum gross economic benefit desired and established by the APAIQ.

Historically, incomes per extractive fishing of the red sea urchin in the study area have been equivalent to those registered for “lapa”. The AMEBRQ annually produces a mean of 28 tons and 6,000 units of “lapa” *Fissurella* sp. and “loco” *C. concholepas*, respectively (AAFQ 1999, personal comm.). Taking into account its normal landed prices ($850/Kg and $700/unit, respectively), related incomes usually reach up to 23 millions from “lapa” and 42 millions from “loco”, and 65 million $/year overall. Projecting a similar economic profit, the target gross income was CLP$23 million/year based on a unit price of CLP$300.

The final restocking programme was based on the introduction of approximately 85,000 2-cm diameter juveniles, produced at the CIMARQ. Although the total amount of seed to be released, calculated on the basis of a minimum recruitment level equal to 40,000 individuals per year (estimated seed stock on the BLS) and a target recruitment equal to 2 times the stock target (120,000 individuals) was 200,000 individuals, the maximum seed available for free was roughly 85,000 juveniles.

Thus, just these individuals were allocated into pre- selected intertidal pools in the area during 2000. This amount was only approved for the first year and subject to review for following periods depending on further quantitative evaluation. Formal arrangements allowed the APAIQ to be provided free of charge of restocking material (seed) and technical support during the project by the CIMARQ.

Management measures were also designed for implementation during the project, based upon historical analysis of previous and current fishery regulations, but also including new complementary measures. Currently, traditional regulations for the red sea urchin along the Chilean coastline establish a minimum legal size of 7 cm diameter and a closed fishing season of 4 months (15 October to 15 January) (Subsecretaria de Pesca, 1999).

In addition to this general measure, the APAIQ agreed to close the fishing ground of the AMEBRQ for the period of the project (4 to 5 years). This closure applies to any sort of fishing practice on sea urchins in the area, including manual extraction, free and scuba-diving. During this period, extraction of sea urchins is allowed only in exceptional cases, restricted to monitoring purposes, and using sampling procedures defined on the evaluation and monitoring programme.

Furthermore, during this period periodical movement, rotation of banks and reallocation of patches was proposed. This procedure starts with the movement of released individuals from intertidal pools to subtidal sectors for on- growing, a process that would be maintained by rotating stocks from abundant patches within optimum substrata and food productive zones. It also was intended to carry out constant movement and redistribution of individuals within each patch at both intertidal and subtidal zones, so as to promote optimal use of food resource and substrata. Under- sized individuals were removed and replaced into better zones, and over- sized individuals (≥ 8.0 cm) were harvested as mean of supporting operational costs.

Finally the evaluation and monitoring study was designed, adapted from the methodological framework specifically developed during the resource evaluation within the BLS. The minimum sampling unit and area, and also a protocol for the sampling plan for *Loxechinus albus* were established and two monitoring sessions were scheduled every year in order to evaluate the state of these and the other benthic resources in the area.

CHAPTER 3

THE BIO-SOCIO-ECONOMIC SIMULATION MODEL (BSESM)

3.1 INTRODUCTION

3.1.1 DYNAMIC SYSTEMS MODELLING

As quoted by Muir (1996), amongst a range of similar descriptions, Webster's dictionary (9^{th} Ed.) defines 'system' as a 'regularly independent group of items forming a unified whole'. The concept of interaction and interconnection implies a number of components that can influence one to another, by means of series of inputs and outputs. The boundaries defining a system are critical in describing the system' s structure, context and nature. Elements inside the boundary form the system structure, which interact to generate the systems characteristics (Muir, 1996).

Systems can be classified according to the existence of flow across its boundaries, into closed and open systems (Muir, 1996). When matter, energy and information neither enters nor leaves the system, but is conserved inside, the system is essentially closed. These systems are typically linear, predictable and ordered.

On the other hand, as most real-world systems, open systems are characterised by a given flow exchanging energy, matter and information with the environment. Major characteristics of these systems are (Davidsen, 1999):

- the dynamic behaviour and relationship between flows and levels;
- the existence of delays or lags in actual systems,
- the occurrence of feed-backs characterized by circular causality, and
- the predominance of non linearities.

As open systems are essentially more complex in terms of structure, their behaviour becomes more difficult to predict. Their characteristics determine that even though a condition of equilibrium may be possible; it is only one among a number of possibilities. Hence, in open systems 'equilibrium can only be described as a dynamic, meta- stable state, where interacting elements maintain a given structure for a given time period' (Muir, 1996).

In order to understand, adapt to and describe systems structures, but mostly to predict their behaviour and take control measures, methods have been increasingly developed to capture reality in formal models by the application of modelling approaches to systems of various types (Bennet and Chorley, 1978; Davidsen, 1999).

Models are a simplified representation of reality, containing only those attributes that are relevant to a particular problem (Leung and El-Gayar, 1997), used to describe and understand the complex systems relationships, which should be used to inform rather than legitimise management or policy decision (Constanza *et al.*, 1993). Hence, a model can be a collection of mathematical equations or rules that describe fundamental relationships between concepts of a system. Simulation models, in particular, can be used as a tool to investigate and characterize the relationship between the structure and behaviour of dynamic systems (Davidsen, 1999).

According to Muir (1996), for models in ecological/economic systems, in which aquaculture and fishery could be included, three criteria could be identified for the evaluation of the models:

- realism (simulating systems behaviour in a quantitatively realistic way);
- precision (quantitatively precise simulation), and
- generality (representing a broad range of system behaviour using the same model)

However, no model can possibly maximize all these goals, and the approach will vary according to the final objective. The final objective of modelling can be divided into three major levels- description, monitoring, and explanation and prediction (Chen, 2000).

There are numerous models and approaches to modelling, and is often useful to distinguish between model types (Table 3.1). These are usually classified into stochastic and deterministic models, dynamic and static models, lumped parameters and distributed parameter models, linear and non linear models, research and management models (Jeffers, 1978; Jogensen, 1983; GESAMP, 1991).

Despite the number of modelling approaches, the modelling and simulation (M&S) process has a specific life cycle, with fundamental phases or guidelines for model development. Fig. 3.1 shows the life cycle in M&S, including also verification, validation and accreditation (VV&A) and testing (VV&T) points to be considered (Balci, 1998).

Table 3.1: Classification of models (modified from Jorgensen (1983) and GESAMP (1991)).

Model type	General description
Empirical models	Derived from large data-sets
Mechanistic models	Derived from theory- deducing
Deterministic models	Predicted values are computed exactly
Stochastic models	Predicted values depend on probability distribution
Static models	The variables defining the system are dependent on time
Dynamic models	The variables defining the system are a function of time and/or space
Lumped models	The parameters are within certain prescribed spatial locations and/or time, considered as constants
Distributed models	The parameters are considered function of time and space
Linear models	First- order equations are consecutively used
Non- linear models	One or more equations are not of the first order
Research models	User for research purposes
Management models	Used as management tools

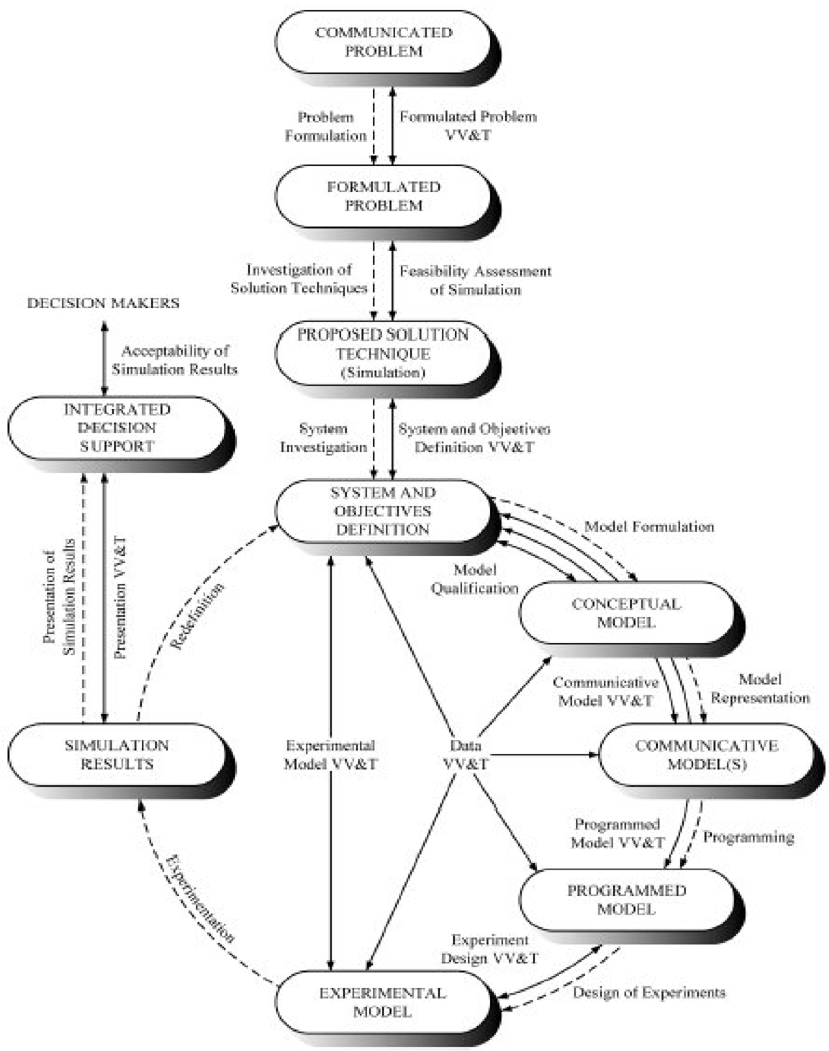


Figure 3.1: Modelling and simulation (M&S) life cycle (extracted from Balci (1998)).

Fishing and aquaculture-based activities on industrial and small-scale can be said to operate as a system, composed of a number of elements, such as: fishing equipment, fleet, facilities, labour force, legal and institutional framework, stocks, markets, etc (Muir, 1996). Dynamic systems science methodology is a useful and robust tool for systematic analysis that can be therefore effectively applied for fisheries management (Manetsch and Park, 1982; Seijo, 1987; 1989, Seijo and Defeo, 1994b; Charles 1995; Seijo *et al.*, 1997).

3.1.2 Bio-socio-economic fishery modelling

'Bio-economics can be defined as the use of mathematical models to relate the biological performance of a production system to its economic and technical constraints' (Allen *et al.*, 1984). If multiple objective, societal goals, human institutional behaviour and dynamics of participating agents are included, the social component takes part of the analysis, through so-called *bio-socio-economic* models (Charles, 1989).

The understanding of a large number of biological, physical, environmental and social factors is essential to the development of a realistic bio-socio-economic model. Dynamic modelling can also be used to deal in a comprehensive manner with sustainable development, the simultaneous pursuit of socio-economic, ecological, community and institutional sustainability (Charles, 1995).

Increasingly, fishery managers and scientists, economists and other social scientists have been involved in the study of fishery systems (e.g. Andersen, 1978; Pringle, 1985; Rettig, 1987). Given the complexity of biological, social and economic issues involved in the management and exploitation of fishery resources, a large number of different applications from policy and strategic analysis to development of computer-based bio-socio-economic models, and quantitative and qualitative information about fishery systems have been produced during past decades.

Many modelling studies focus on the problem of complexity, and solutions have been proposed in the attempt to solve one or other specific aspect. Among these, is a call for the use of scale- models, based on a simplified representation of every constituting element: constituents, transfers, interactions, environments, driving forces, etc (le Fur, 1999). The integration of these elements within a simulation scale-model permits on reconstruction of the complexity of the system under study, without an intervening formalization. Furthermore it allows the exploration of the system's behaviour, intelligent prediction to be made about the consequences of various management strategies, what if scenarios to be conducted, and the possibility to put together knowledge from theoretical, laboratory, and field studies into a consistent whole to identify areas where knowledge is lacking, sparse or inconsistent (Cuenco, 1989; Le Fur, 1999). Among others, these are the major reasons why systems modelling approach is useful to model and analyse aquaculture-based and fishery related systems, this without risk of damaging the real system.

According to Seijo *et al.*, (1997), a systems approach to fisheries management should consider the following sequential stages):

- Clear definition of fishery data requirements.
- Characterization of the fishery in terms of the resource dynamics, potential ecologic and technologic interactions, effective capture effort, and instruments feasible of being implemented.
- Mathematical modelling of the interactions between the various fishery components.
- Primary and secondary data collection for estimation of relevant model parameters.
- Computer model development for numerical representation and solving the model.
- Stability, error and sensitivity analysis of the model run on the computer.
- Model validation, based on statistical comparison of real-system observations and model outputs.
- Evaluation of potential bio-economic impact of alternative management strategies, and if required, integration of the model with optimisation algorithms (linear or non-linear) based on single and multiple criteria, for design of robust strategies, to minimize the difference between the resource manager's expectations and the model's outputs.

Quantitative dynamic modelling of fishery systems plays an important role in the process of developing and analysing bio-socio-economic policies. Hence models provide quantitative laboratories to test and evaluate possible policies before they are implemented in the real world (Charles, 1995). Simulation tools descending from artificial intelligence allow the application of this approach to fishery systems, and the development of scale-models simulating these components (e.g. marine populations, fleets, markets, societies, management systems, economic sectors, etc) (le Fur, 1999). The role of modelling in all the cases is to avoid the costly and time-consuming trial and error process of deriving and implementing full-scale, but untested approaches (Charles, 1995).

3.1.3 FACTORS INFLUENCING FISHERIES STOCK ENHANCEMENT

Being the major approach for stock enhancement, restocking has been defined as a technique whose objective is the compensation of depleted natural resources and/or conservation of stock species threatened with extinction (Bannister, 1991; Welcomme, 1998).

Stock enhancement and the creation of culture-based fisheries are aimed at a combination of three elements of sustainability- economic, social and environmental. Though essentially a resource management procedure, it has a stronger base of environmental improvement (Pillay, 1997). For this, restocking activities rely on a number of biological, technological, economic and social aspects, whose combination determines the ultimate success or failure of the activity.

Stocking enhancement activities are based on the release of hatchery-reared larvae and/or juveniles into their natural habitat, where they participate in the ecological processes, which model natural populations and communities. This implies that the effectiveness of any restocking programme is subjected to thorough understanding of the effects that the activity produces on the ecosystem in which intervenes (Picketty, 1981). Thus, the success of a restocking activity in a given coastal area relies on careful consideration of the major biological factors regulating the species and community (Lepez, 1988). Likewise, enhancement efforts which do not address the stages that limit production, are not likely to be successful; e.g. seeding of juveniles will do little for a population limited by survival of middle- sized animals or food supply (Tenger, 1989).

When a restocking programme is performed the number of adults in a given time would be the resultant addition of natural and artificial recruitment coming from the enhancement activities and the remaining adults in the population (Fig. 3.2) (Begon *et al.*, 1996). Despite this contribution, the incoming stock constitutes an ecological perturbation to the community and its populations (Fig. 3.3) (Lepez, 1988). Major potential alterations are determined by changes in competence patterns with other species that rely on the same food resource and/or substrata.

From an ecological standpoint, Lepez (1988) identified a number of factors (Table 3.2), which should be accounted for to ensure success and effectiveness of these practices. Some are likely to vary with local and regional scales; and therefore special attention must be given to the identification and determination of the specific biological parameters for the species and the study area.

Table 3.2: Biological factors to take into consideration in a restocking exercise**.**

Population biology	Community
Reproductive strategy	Productivity of coastal area and biomass of major food resource of the specie.
Recruitment periods	Denso-dependent processes
Juvenile habitat characterization	Role of the species in the community, such as trophic relations predator-prey, inter-specific competition
Larval dispersion patterns, depending on the species	
Dietary items and feeding habits	
Interactions between adults and juveniles	
Suitable density of recruits according to the food resource available	
Migration patterns	

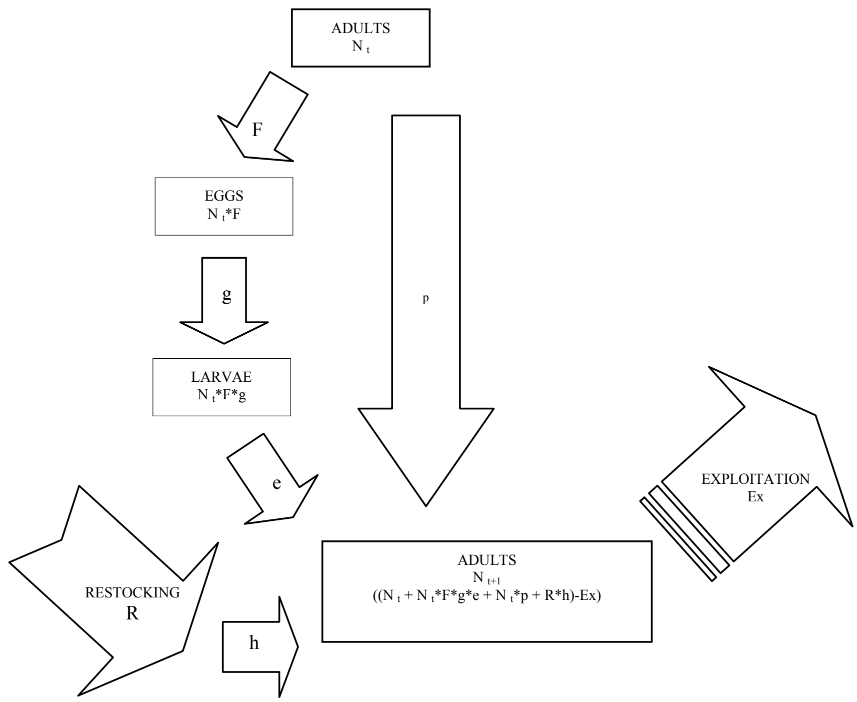


Figure 3.2: Processes involved in the determination of the number of individuals in a population subject to external intervention from man, F: fecundity; g, e, h and p: survival rates, (Modified from Begon *et al*., 1996).

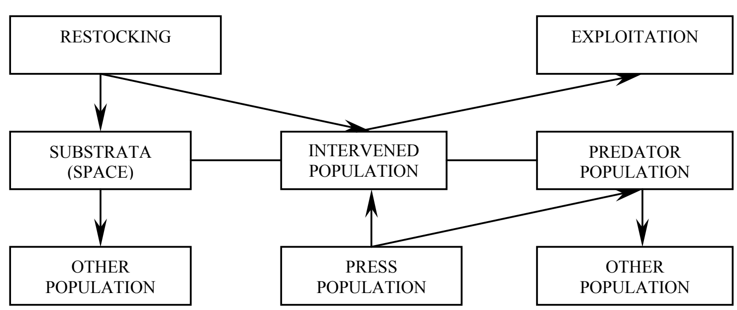


Figure 3.3: Interactions of a population subject to external intervention with the other populations appearing to the same community (modified from Lepez (1988)).

Normally, technical and productive related aspects to be considered in restocking strategies are: size of the fry or seed, restocking density, biomass, restocking period and planting season, transportation to stocking location, mechanism of release or seeding, recapture operations and monitoring procedures (Cowx, 1994; Welcomme, 1998).

Despite its potentially conservational role, stock enhancement and the creation of new fishery resources has failed to muster public support till its economic benefits could be demonstrated (Pillay, 1997). The common lack of economic considerations in the design and evaluation of restocking is probably the reason for insufficient return rates in most cases, though restocking in many freshwater reservoirs is demonstrably cost-effective (Welcomme, 1998). The situation of marine systems is less clear and reported information suggests too low levels of cost-effectiveness to warrant these techniques as a major tool of management (Welcomme, 1996; 1998; Cowx, 1998).

In these circumstances even with its potential as a conservation measure for reviving valuable stocks, stock enhancement is presently dependent on economic viability for attaining public acceptance and becoming sustainable (Pillay, 1997).

According to Langton and Wilson (1998), economic viability of any enhancement programme is determined by economic, but also by biological variables influencing the first. The first group is primarily composed of:

- costs of eggs, larvae, fry or seed (stocking material);
- costs of capture and maintenance of broodstock, and
- capital and operational costs of the hatchery.

In second term, biological variables are referred to:

- stocking costs;
- mortality;
- growth rate in controlled and natural environment,
- harvesting costs;
- recapture costs and rates, and
- protecting regulations for stocked fisheries.

In the economic design of a restocking model, economic as well as biological variables should be clearly identified and balanced with special consideration on their impact on the costs and revenue generation of the programme.

When considering restocking of commercial marine resources, the product has a defined market value. In these conditions, formal cost- benefit analysis can be applied using different measures of economic profitability. Among these, economists generally use one of two approaches- Net Present Value (NPV) and Internal Rate of Return (IRR) (Langton and Wilson, 1998). Both measures are designed to compare the project in question with the performance of other investments and are based on time discounting of money (e.g.: standard target return at discount rate).

The NPV (Eq. 3.1) compares investment in the project against the rate of return that the investor thinks could expect in the best alternative use of the money. This index gives the estimated present value of the stream of returns and costs, and is calculated by the sum over time of discounted costs and benefits:

$$\mathbf{NPV = II + [(C_1 + R_1)]/(1 + r)] + [(C_2 + R_2)]/(1 + r)^2] + \ldots + [(C_n + R_n)]/(1 + r)^n]} \qquad \textbf{[Equation 3.1]}$$

, where II: initial investment outlay (negative value), n: periods from the initiation of the project, C_n: costs of the project in the period n; R_n: revenue of the project in the period n, and r: rate of return expected for the project.

The calculation for the IRR uses the same equation, but it determines an internal rate of return r so that NPV equals zero, so this value can be compared with the rate of return of alternative projects. Both methods are basically used to pre- evaluate projects; but can also be performed to evaluate results as the programme develops.

Although, financial return is a function of previously mentioned biological processes, the real production of the system (proportion of fish stocked which are actually harvested) and the given price per fish are also predominant variables in the final economic results of the restocking project (Welcomme, 1996).

While considering an acceptable degree of uncertain of these variables, in a theoretical model of economic viability, if seed or fry production costs are fixed (technically given), the equilibrium point between restocking costs and corresponding revenue varies in terms of the recapture rate and the price per captured individual (Kaze and Bailly, 1991). If the recapture rate is high and price is acceptable, the costs per released unit decrease, but when the species is highly valuable, recapture rates have less influence on the overall viability of the restocking project. These relations represent the equilibrium line between costs and benefits, which delimits the theoretical viability zone of restocking aquaculture programs.

Interrelations between demand and product price play an important role in the economic evaluation of profits (Kaze and Bailly, 1991). Dealing with inelastic demand implies that increases in capture rates would cause strong decreases in marginal benefits. In the contrary, in case of elastic relations, the viability would increase.

Enhancement activities must consider socio-economic sustainability; they must therefore rely on a number of societal factors directly determined by socio-economic sectors and agents involved and their societal needs and expectations, and the legal and institutional framework regulating the system.

Socio-economic sustainability involves maintaining or enhancing socio-economic welfare, which is to generate suitably distributed benefits and maintain overall viability in local and global economies (Charles, 1994). This can be measured at both individual level and aggregated form across the resource system.

Needs and expectations of participating agents and sectors are achieved at a group level within the concept of community sustainability, recognizing that a community is more than a collection of individuals.

The legal and institutional framework must be suitable to finance, administrate and organize over the long-term, which is a prerequisite for suitability of the other components. Hence to manage stock enhancement, in addition to managing biological systems, it is also necessary to manage the investment. Here, apart from the important relationship between investment and economic return, is introduced the need for institutions to handle questions of access and property rights (Hallenstvedt, 1999).

The ownership issue is probably one of the most relevant institutional factors determining the system. In open systems, like large rivers, lakes or coastal areas, ownership is not always well defined (Cowx, 1998). In many countries, fisheries resources are legally defined as common property with open access. However, several experiences have shown that this kind of exploitation leads to excess fishing capacity and dissipation of resource rents (Ferrer, 1989). This is the reason why many ranching programmes do not success in financial terms (Cowx, 1998). Resource allocation through territorial rights in fisheries may be the way to overcome this problem. Likewise, community-based management and/or licensing systems may also offer potentially useful strategies for this regulatory control.

Large-scale enhancement programmes must be launched as socially and institutionally integrated projects, e.g.: integrated with the traditional use of marine resources (Hallenstvedt, 1999). Besides, any restocking project must be implemented in conjunction with proper management plans of the resource. Among these plans, measures to consider include selective harvest or catch at a minimum size or weight; closed season; setting up of "marine sanctuaries", etc. (Trinidad-Roa, 1989). Development of sea ranching and stock enhancement will increasingly rely on existing and evolving local and regional institutions in the coastal area (Hallenstvedt, 1999).

In an attempt to cover the large number of factors of different trends influencing restocking and management of benthic resources, the following diagram is indented to list and put them together as whole system (Fig. 3.4).

3.2 OBJECTIVES

The aim of modelling this system was to generate a dynamic and interactive simulation model, which allows resource managers to analyse the biological effects and economic outputs of different integrated restocking and management strategies. This software was specifically designed for the red sea urchin, and was developed to operate under the framework of the Chilean system of areas of management and exploitation of benthic resources.

The model was intended to be a user-friendly tool that could provide quantitative data, projections of scenarios and graphical outputs to support decision- making processes in management and exploitation planning. It was therefore designed as far as possible to use minimum, standardized and available input data, be simple to use and operate on a normal Windows-based desktop or laptop computer, producing graphical and tabular quantitative results for a number of key biological, and socio-economic representative parameters and evaluation indices. The major objectives of this chapter could therefore be summarized as to:

- identify and describe the major factors, which regulate biological processes, technical-productive activities, socio- economic projections and spatially- referenced processes, which in term determine the overall outcomes, and ultimately the success or failure of a restocking programme and/or management plan for the red sea urchin.

- identify interrelations between various factors involved, design the functional structure, deduce mathematical equations describing interrelations and develop a submodel-structured interactive simulation model of the system.

The following sections are focused on the modelling methodology and a comprehensive description of major components, of the theories and underlying assumptions in the model, its representation of the problem entity, structure, logic, and mathematical and causal relations. The final section presents a thorough analysis of the model's conceptual structure, computer programming and implementation into the final software.

3.3 MATERIAL AND METHODS

3.3.1 THE MODEL-MAKING PLATFORM SOFTWARE

The base software used for the design and construction of the bio-socio-economic simulation model was Powersim Constructor 2.51®, available within the Powersim Academic Kit® (PAK), which also incorporates the Powersim Solver 2.0® workbench for model analysis and optimisation.

This software is a powerful model-maker for creating, analysing business processes and competitive markets, to demonstrate strategies and identify leverage points for managing change. A model created can be used as the basis for simulation and allows importing historical information, experimenting with future scenarios and developing long-term strategies. Models can contain up to 750 variables or 3,000 variable elements in their structure. It has model design features, such as casual loop diagramming, and it supports level and rate modelling. A separate user interface can be designed that allows users to interact with the model without being aware of its presence (Anonymous, 1999).

Though this software was designed for business modelling, its extremely powerful abilities to model dynamic systems based on stocks and inventories of elements, led to its choice for modelling these more complex and interconnected systems.

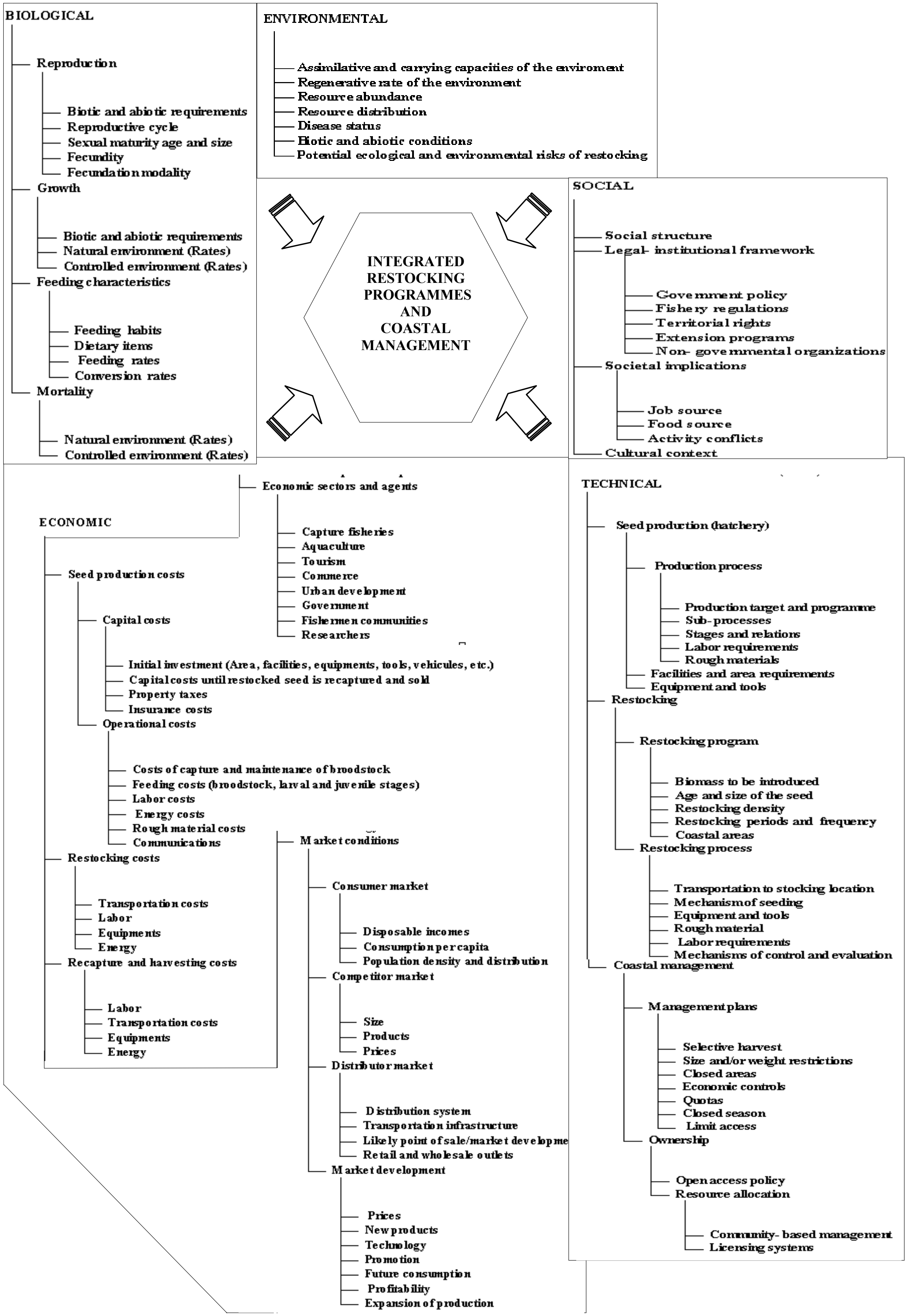


Figure 3.4: List of major factors influencing restocking and coastal management activities of benthic resources in Chile.

3.3.2 HARDWARE

Table 3.3 details the major equipment and computing systems used in the course of the research. These materials were used during both, the bio-socio-economic and the GIS-based modelling stages undertaken at the facilities of the Geographical Information Systems and Applied Physiology (GISAP) laboratory in the Institute of Aquaculture, University of Stirling.

Table 3.3: Computing systems and equipment used during the development of this work.

Equipment	Model and technical specifications	Use
Desktop computer 1	HiGrade; Windows NT 4; 128 K RAM; Axion Pv- 200 pro; 4.0 + 8.0 Gb HDD; 21'' Iyama visionmaster	Platform system
Desktop computer 2	Clone; Windows NT 4; 64 Mb RAM; P5- 133; 4.0 Gb HDD; 19'' screen	Scanning routines and backing up data (CD and cassette)
Laptop computer 1	Dell Inspiron 3700; Windows 98; 128; Mb RAM; Intel Celeron processor 450 MHz; 4.8 Gb HDD; 12'' screen	Parallel systems
Laptop computer 2	Dell Inspiron 2500; Windows XP; 128 Mb RAM; Intel Pentium III processor 1 GHz; 20 Gb HDD; 14'' screen	
Server	Dell Poweredge 1300; Windows 2000; 256 Mb RAM; Intel Pentium III processor 800 MHz; 108 Gb HDD	Data backup and file storage
Scanner	HP 3c	Scanning
Printer 1	LaserJet 4 Plus	Black and white base printer
Printer 2	HP DeskJet 500C	Colour printing
Camera 1	Cannon Sure Shot; Automatic; 38- 60 mm;	General use
Camera 2	Fuji Axia Ix-10; Digital	

3.3.3 DEFINITION OF THE SYSTEM PHYSICAL BOUNDARIES AND TIME-PERIOD

The physical limits, therefore the boundaries of the system, were defined in accordance with the geographical coordinates delimiting any Area of Management and Exploitation of Benthic Resources (AMEBR). This allows the system to be spatially scaled and linked to a known geographic location. The time-period on which the model was set out was defined as a maximum of 15 years, with a one- year fixed time-step, starting on year 0.

3.3.4 IDENTIFICATION AND SELECTION OF DETERMINANT FACTORS IN THE SYSTEM

Preliminary identification of the major factors in the system was carried out mostly on a theoretical basis by means of bibliographic reviews. These factors were listed and described in detail in order to determine various aspects such as their influence and scale of action (direct or indirect, primary or secondary, etc.), measurability, relative weight, and current availability of associated quantitative data and qualitative information.

Final selection of determinant factors was undertaken by establishing a comparative analysis between the factors identified, and those present and observed in various forms in the real system studied. Data gathering and the observation and characterization of activities during the fieldwork stage supported this process. At this point, most generalisations from literature were reduced to specific factors interacting within the framework of the system of AMEBR and the artisanal fishing sub-sector in Chile. Furthermore, special attention and priority was given to those factors, which could be quantitatively measured in real terms, hence having potential in running the simulation model in the final stages within the modelling process.

Even though this selection process aimed to achieve the best representation of the real system, by including as many determinant factors as possible, it was also focused on the development of a clear and logically structured model. This implied a narrower, specific, objective-oriented selection process, which reduced the number of factors, aiming to achieve a correct balance between essential input requirements, data availability, and quantitative measurability.

Although the selection process was mainly carried out at this stage, a number of inclusions, exclusions and modifications of factors, or their influence and treatments, was done during the design and construction stages, up to the final revision and testing stage.

3.3.5 CLASSIFICATION AND AGGREGATION OF FACTORS, AND GENERATION OF SUBMODELS

Following identification and selection, factors were classified according to the nature of their action, participation and/or influence into the system. The major classes defined the submodels of the system.

The process of classification and aggregation of determinant factors resulted in the base conceptual model, formed from submodels. This process was further developed using sequential schematic and graphical representation of various types and forms, considering different modelling approaches, linking and weighting systems.

Table 3.4 lists all the groups of factors and its major components that were identified during this process, where the factors selected and explicitly considered in the model are highlighted in bold. This constitutes a thorough review of major factors influencing restocking activities and coastal management of the red sea urchin in the system of AMEBR in Chile.

Table 3.4: Group of factors in the conceptual model relevant to the management and restocking of red sea urchins in Chile.

Group	Factors	Components
A. Biological	i. Resource abundance	**1. Population size**
		2. Size/age distribution
	ii. Life cycle and reproduction	**3. Sexual maturity age and size**
		4. Reproductive cycle
		5. Natural recruitment periods
		6. Adult-juvenile interactions
		7. Migration patterns
		8. Limiting life stage of the species
	iii. Growth	**9. Parameters**
		10. Weight-length relations
	iv. Feeding and ecological role	11. Habits
		12. Strategy
		13. Dietary items
	v. Permanency, survival and inter-specific relations	**14. Natural rates**
		15. Trophic role
		16. Density-dependent processes
		17. Inter-specific competition
		18. Prey-predator relations
	vi. Natural repopulation	**19. Recruitment variability**
		20. Recruitment patterns
		21. Recruitment rates
B. Production	i. Production process	1. Seed production
		2. Restocking
		3. Resource evaluation
		4. Recapture
		5. Harvest and sale
	ii. Production plan	**6. Production targets**
		7. Periods
	iii. Restocking exercise	**8. Biomass/number to be released**
		9. Age and size of seed
		10. Restocking periods/frequency
		11. Coastal areas and restocking site selection
		12. Transportation
		13. Seeding mechanism
		14. Equipment and tools
		15. Inputs and labour force
	iv. Labour requirements	16. Seed production
		17. Restocking
		18. Resource evaluation
		19. **Recapture**
		20. Harvest and sale

Cont. **Table 3.4**

C. Socio-economic	i.	Seed production costs	1. Initial investment
			2. Capital costs
			3. Labour costs
			4. Energy costs
			5. Input costs
	ii.	Coastal property costs	**6. AMEBR taxes**
	iii.	Restocking costs	**7. Fleet opportunity fishing costs**
			8. Cost of the seed
			9. Labour costs
	iv.	Resource evaluation costs	**10. Fleet opportunity fishing costs**
			11. Technical support costs
	v.	Recapture costs	**12. Capital costs**
			13. Operational fishing costs
	vi.	Product	**14. Objective market**
			15. Price
			16. Productive level
			17. Historical incomes
	vii.	Market	**18. Types**
			19. Sizes
			20. Preferences
			21. Development and projection
	viii.	Benthic resources	**22. Historical commercial importance**
			23. Specific-generated incomes
			24. **Bio-economic interrelations**
	ix.	Economic sectors and agents	**25. Fishermen community**
			26. Government (Undersecretary of Fisheries)
			27. Aquaculture
			28. Seed suppliers
			29. Research institutions
	x.	Legal-institutional framework	30. Government policy
			31. Fishery regulations
			32. Territorial rights
	xi.	Societal implications	**33. Requirements and expectations**
			34. Job source
D. Spatial	i.	Habitat	**1. Geographical distribution**
			2. Physical characteristics
			3. Biological characteristics
			4. Sites suitability
			5. Area availability
			6. Assimilative and carrying capacities
			7. Potential ecological risks of restocking
	ii.	Resource distribution	8. Distribution patterns
			9. Distribution zones
			10. Distribution density
			11. Coverage process
			12. Other benthic resources

3.3.6 CONSTRUCTION OF THE FUNCTIONAL STRUCTURE AND MATHEMATICAL EQUATIONS OF SUBMODELS

The next modelling stage focused on the construction of the model' s structural design and mathematical equations. From this stage onwards, dynamic modelling of the system was developed using Powersim Constructor 2.51® (Anonymous, 1999), as formerly described.

This software utilizes a language which purpose is to make a description, or to model, of an imaginary or real system. For this, it is provided with a diagram editor for defining simulation models (Fig. 3.5), where variables or factors are represented as graphical objects, which may be connected using links and flows. Each link and flow represents the relationship between the variables linked, which exact definition is defined as an equation in Powersim language.

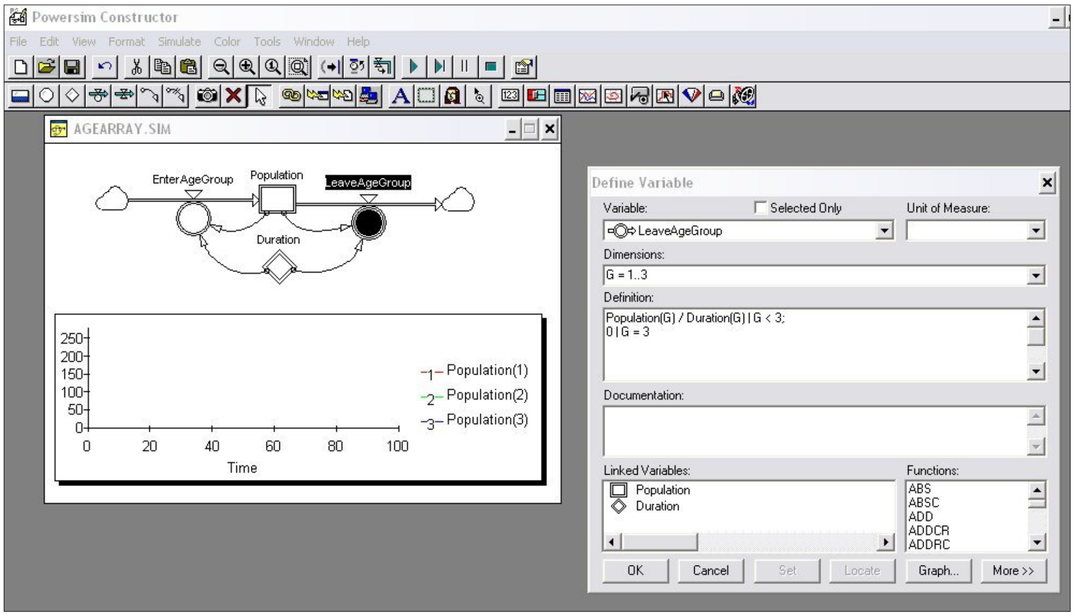


Figure 3.5: Example of model building showing the diagram editor and the 'define-variable' window for model and equation construction available on Powersim.

Building blocks used in constructing models with this software are basically five: levels (stocks), flows, auxiliaries, constants, and links. In addition, auxiliaries can be paired with flows to create flows-with-rates, and links can be categorized as information links, delayed links, and initialisation links (Anonymous, 1999).

The first step was to determine and select stocks or *levels*, constant variables or *constants*, and variable elements or *auxiliaries*, among the factors. This process involved detailed revision of, the characteristics of each factor and more importantly its nature, specific role, direct incidence and priority order in the system.

The second step in the logical design sequence was to define the relevant levels in the system (e.g.: wild stock population), in terms of dimension and ranges (e.g.: 10 substocks with 12 size-classes/each). Hence, modelling of the system was undertaken using an array variable-based approach; using dimensioned variables or array elements influenced by scalars and/or vectors (one-dimension array).

Next, each level was linked by a number of determinant factors or variables, these being constants (primary and independent factors; e.g.: von Bertalanffy growth constant K) or/and auxiliaries (secondary and dependent variables generated by the combination of two or more constant variables). These elements were also dimensioned according to the level's dimension and ranges when required and linked to them by means of different types of links, such as direct or delayed links, causal loops, etc.

Dynamic changes in constituent elements of levels were created by the use rate-defined input and output flows. Input and output flows were correspondingly dimensioned, and conditioned by the interaction of external constants and auxiliaries.

Once every constant, auxiliary and level was inter-connected by means of different links forming-up the functional structure of each submodel, the following process was orientated towards the deduction and construction of the mathematical functions describing these interactions. Hence, a mathematical equation between the correlated elements was deduced and modelled, built and introduced into each and every link in the functional structure. To carry this out, a number of functions working with arrays, and also built- in, such as the arithmetic, logic, economic and financial, graph, history, conditional, time-related, delay, control and miscellaneous functions available in the model-making software platform were used. As Powersim Constructor supports a huge number of functions, the functions listed on next table are limited to those most used during this study.

Table 3.5: Major functions used for development of the BSESM (modified from Anonymous, 1999).

Group	Function
Array Functions that utilize one or more arguments which are arrays	ARRSUM - Sum of Array Elements VECTOR - Create Vector
Built-in Functions that are part of the simulation language	| - Guard Operator ; - Constraint operator AND - Conjunction, Logical And BUT - Constraint operator FIRST - Get Lower Limit of Range or Base Range of Index LAST - Get Upper Limit of Range or Base Range of Index OTHERWISE - Default Guard Operator SUM - Sum of Expressions Over Indices WHEN - Guard Operator
Conditional Functions that perform different tasks, based on conditions passed as arguments	IF - Arithmetic If

Cont. **Table 3.5**

Group	Function
Control Functions used to control a simulation run.	PAUSEIF - Conditional Pause PAUSEWHILE - Continuing Pause STOPIF - Stop Simulation STOPRUNIF - Stop Current Run
Delay Functions that imply a delayed influence.	DELAYINF - N-th Order Information Delay DELAYMTR - N-th Order Material Delay
Financial Functions that compute present value, future value, and periodic payments	NPV - Net Present Value PMT - Periodic Payment
Graph Functions whose results are tabulated for given input values	GRAPH - Linear Graph with Horizontal Asymptotes GRAPHCURVE - Polynomial Graph with Linear Asymptotes GRAPHLINAS - Linear Graph with Linear Asymptotes GRAPHSTEP - Horizontal Graph with Horizontal Asymptotes
Logical Functions returning a logical value representing True or False	< - Less Than <= - Less Than or Equal To <> - Not Equal To = - Equal To > - Greater Than >= - Greater Than or Equal To AND - Conjunction, Logical And FALSE - Logical False NOT - Negation OR - Logical Or TRUE - Logical True
Mathematical A function group containing all kinds of mathematical calculations	^ - Number Raised to a Power % - Percent * - Multiplication + - Addition - Subtraction / - Division ABS - Absolute Value ADD - Sum of arrays ARRPROD - Product of Array Elements ARRSUM - Sum of Array Elements LN - Natural Logarithm LOG - Base N Logarithm MATRIXPROD - Matrix Product SPROD - Scalar Vector Product SQRT - Square Root
Statistical Functions that perform computations on a set of data provided as arguments	ARRAVG - Average of Array Elements ARRMAX - Maximum of Array Elements ARRMIN - Minimum of Array Elements AVG - Average MAX - Maximum MIN - Minimum
Time Related Functions that utilize parameters or return values that are expressed in the time unit of the simulation	STARTTIME - Start Time of Simulation STOPTIME - Stop Time of Simulation TIME - Current Time of Simulation TIMESTEP - Time Step of Simulation ATSTART - Test for Beginning of Simulation PULSE - Periodic Pulse RAMP - Linear Function STEP - Step Function

3.3.7 INTEGRATION OF SUBMODELS AND GENERATION OF THE FINAL MODEL

In order to integrate the submodels previously designed, dimensioned and constructed, key factors were copied from one into the other, linking them dynamically through their functional structure and mathematical equations.

These specific variables were very important linking factors between subsystems; in terms of input data and/or output data flows. These could either be initial input variables, affecting and regulating elements in one or more submodels, and/or output- auxiliaries generated in one submodel and controlling one or more others.

These dynamic objects also allowed the integration of all constituent submodels into one whole system, operating under identical conditions, such as the same time-step, spatial scale and geographic boundaries, system dimension, and critical assumptions. This also implied the occurrence of dynamic input, output and feedback, regulating the processes and data transfers between the submodels when running any simulation routine.

3.3.8 SELECTION OF CHANGEABLE AND FIXED INPUT VARIABLES

Before user-interface windows for input were created, a given group of inputs in the system were set as fixed variables, i.e. constants. These were mainly secondary inputs, functional and structural links and conversion constants that the user does not need to change or see, and were set as constant values, neither accessible nor changeable during any simulation trial.

Remaining inputs (determinant variables) were again aggregated, this time strictly in accordance to their nature and role in each submodel. These were re-grouped, in order to generate a simple, but also applied, precise and general model, for accessible operation to a wide spectrum of users.

3.3.9 DEFINITION OF UNITS, RANGES, DESIGN AND CONSTRUCTION OF INPUT WINDOWS

Units of measure were primarily defined according to the metric system (meters, kilograms, etc). However, general and self- explanatory units of measure (fishing units, labour force units, units, individuals/year, etc) were also generated. At this stage, a detailed dimensional analysis was carried out in order to ensure correct compatibility between variables and units of measure used in each case, so as to obtain consistent results.

The maximum range of variation for each input variable was also defined by their extreme lower minimum and upper maximum values observed for the factor in the system. This was in order to avoid inconsistent results or indeterminate values being generated when running the simulation software. However, all ranges were fairly wide allowing the user to move within a broad spectrum of input values and scenarios, if required.

Input windows were designed to be clear, self-explanatory and simple to operate. To do so, all input data windows were identified by titles, subtitles and legends, describing the variables involved in terms of classes, groups and factors. Each input variable included an input bar-button and value-box for inputting and varying the value, grading scale lines, range of variation and units considered.

3.3.10 DESIGN AND CONSTRUCTION OF OUTPUT WINDOWS

Outputs were selected principally in accordance with standard types of tabular and graphic results describing population dynamics, and economic evaluations. Additional output representations were also included in order to provide the most information, and the best quantitative data support for decision-making processes.

As for the inputs, output measurement units were generated from the pre-established system, and their ranges were set to be automatically scaled by the values obtained in the simulation.

Output windows were designed forming various combinations of time-series tables, frames, value-boxes, charts, and graphical representations such as histograms, and time-series line graphs.

3.3.11 FINAL REVISION, SYSTEMATISATION, ACCESS SECURITY, EDIT AND SAVE

Detailed review and correction of the simulation software was carried out firstly focused on functional structure and design of the model, and secondly on the mathematic equations and functions constructed.

This was done by crosschecking all the relevant connecting links considering real values, and by dimensional analysis. This process was followed by several tests undertaken using limiting and critical values to evaluate the model functionality, flexibility, and potential failures due to mathematical errors, inconsistencies, unlinked or undefined variables and constants.

Functional systematisation of the software was achieved after all required revision routines and crosschecking procedures. In this process, the software was again tested several times, and data input, running, output generation, extraction and printing routines were systematized in a logical order.

Finally, accessibility, editing and saving privileges were defined and set to specific user-levels. These allowed the use of the software to be restricted by means of password security settings, disabling any editing options, either of the model structure or the interactive windows, but allowing data input, running, output generation and data saving during simulation routines.

3.4 RESULTS

3.4.1 GENERAL DESCRIPTION OF THE MODEL

In principle, the BSESM was designed as a model describing the state and dynamics of stocks and production, spatial coverage processes and the socio-economic outcomes of management and exploitation potentially applied to a red sea urchin fishery in Chile.

The model assumes that stocks are regulated by inputs (e.g. growth, natural recruitment, restocking), outputs (e.g. natural mortality, fishing mortality), and processes, linking input and output, such as biological and spatial processes, fishing operations, production projections and socio-economic factors.

The simulation model can be operated with or without including a restocking programme in the management approach. The model also allows the user to include or not, and also to regulate exploitation pressure on the commercial stock available in the system. This allows the flexible study and analysis of multiple macro-scenarios, which may or not include restocking exercises on the areas, as well as levels of exploitation, or even a mixture of both alternatives within the management plan, varying in influence and intensity in time.

Four separate, but linked submodels were integrated into the final version of the simulation model (Fig. 3.6):

- Biological submodel- describing the stock component dynamics and projections.
- Production submodel- relating socio-economic requirements to commercial and production targets of the system.

- Socio- economic submodel- introducing socio-economic requirements and producing a financial evaluation of the project.
- Spatial submodel- processing restocking sites suitability and availability, and their spatial dynamics as restocking takes place.

The diagram below shows a schematic view of the model structure, where the arrows represent the flows from model inputs (in red), to produce intermediate outputs generated from the submodels (in blue), the links and feedback between submodels (in black) and major outputs (in green) resulting from the BSESM.

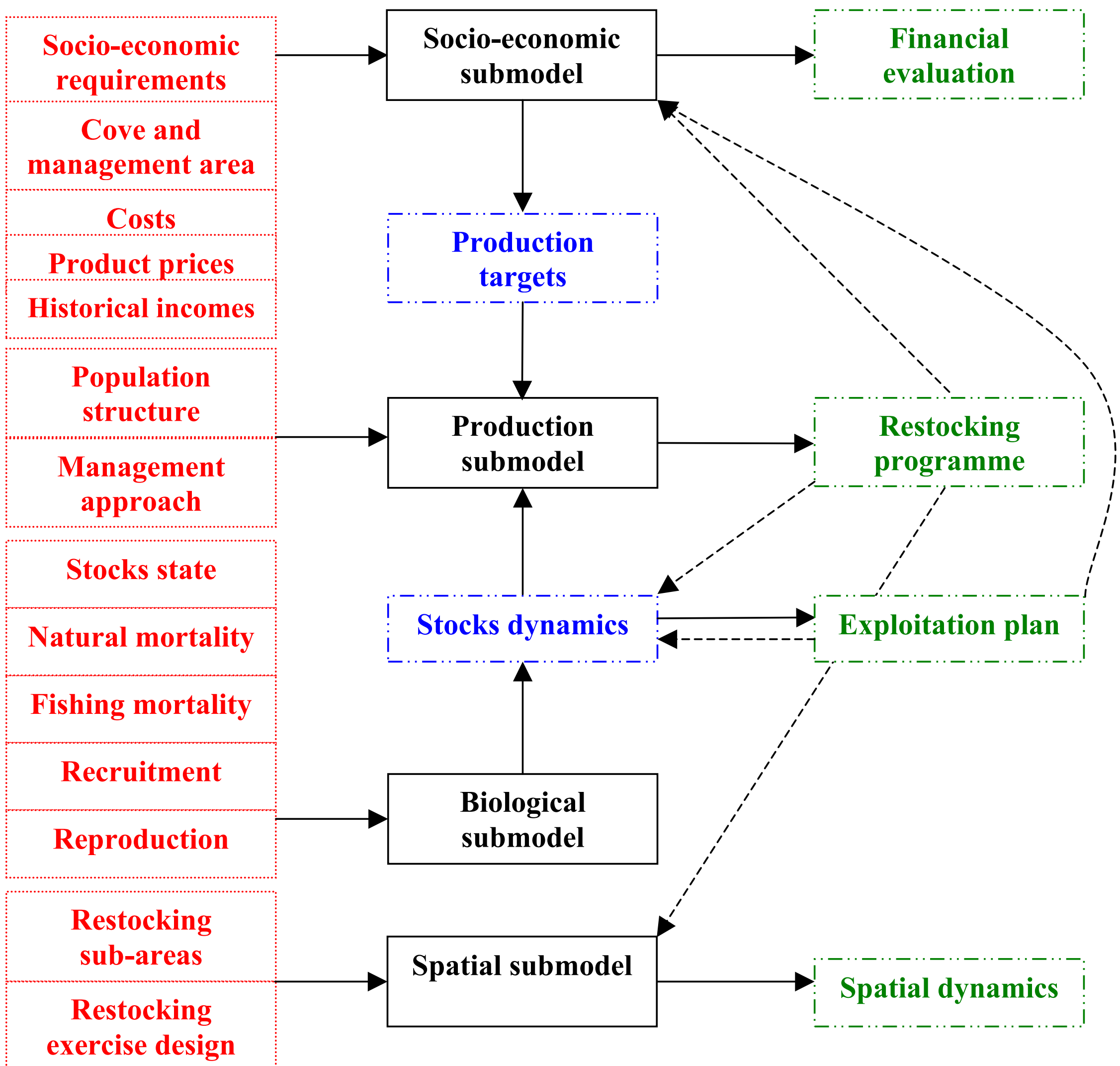


Figure 3.6: General structure of the bio-socio-economic simulation model (BSESM).

Each submodel contributes with a given number of variables and equations in the system, though several variables may be shared between them. On the same extent, they work under identical time- steps, system boundaries and assumptions. Table 3.6 shows the working macro-conditions of the system modelled.

The following sections give detailed descriptions of each submodel goal, specific variables, links and flows, functional structure, and a selection of its major mathematical equations. In addition to this, input variables and procedures, graphical outputs and simulated results generated from running the software are described. The final section aims to present the user with guidelines for the correct use and operation of the software created.

Table 3.6: System's working conditions.

Legal- institutional framework	Areas of Management and Exploitation of Benthic Resources (AMEBR) for small-scale fisheries in Chile (Servicio Nacional de Pesca, 1999)
Boundaries	Geographic coordinates delimiting a given AMEBR
Physical extent	Total water body and seabed covered by the lease, and nearby shoreline region
Time step	Fixed period of 1 year
Start time	Year 0
End time	Year 15
Total evaluation time	Period of 15 years

3.4.2 THE BIOLOGICAL SUBMODEL

The goal of this submodel was to reflect and reproduce the biological effects and dynamic changes in those stocks forming part of the populations involved in different management and exploitation plans.

To facilitate a better understanding and analysis of the biological subsystem, this submodel is structured in two modules- the wild and the released stock. The first is constituted by all natural individuals of the same species co-existing in the system, and the second is formed by a virtual population of hatchery-reared individuals eventually introduced into the system through restocking exercises.

Biological submodel components are linked through specific factors and share some constants (Fig. 3.7). Both components are represented in the form of levels of the system; hence inventories of individuals forming each stock population. These levels are dynamically fed by input flows and simultaneously extracted by output flow-rates. In addition to this, the input and output flows are inter- connected, thus controlling the absolute amount of data flowing through each level.

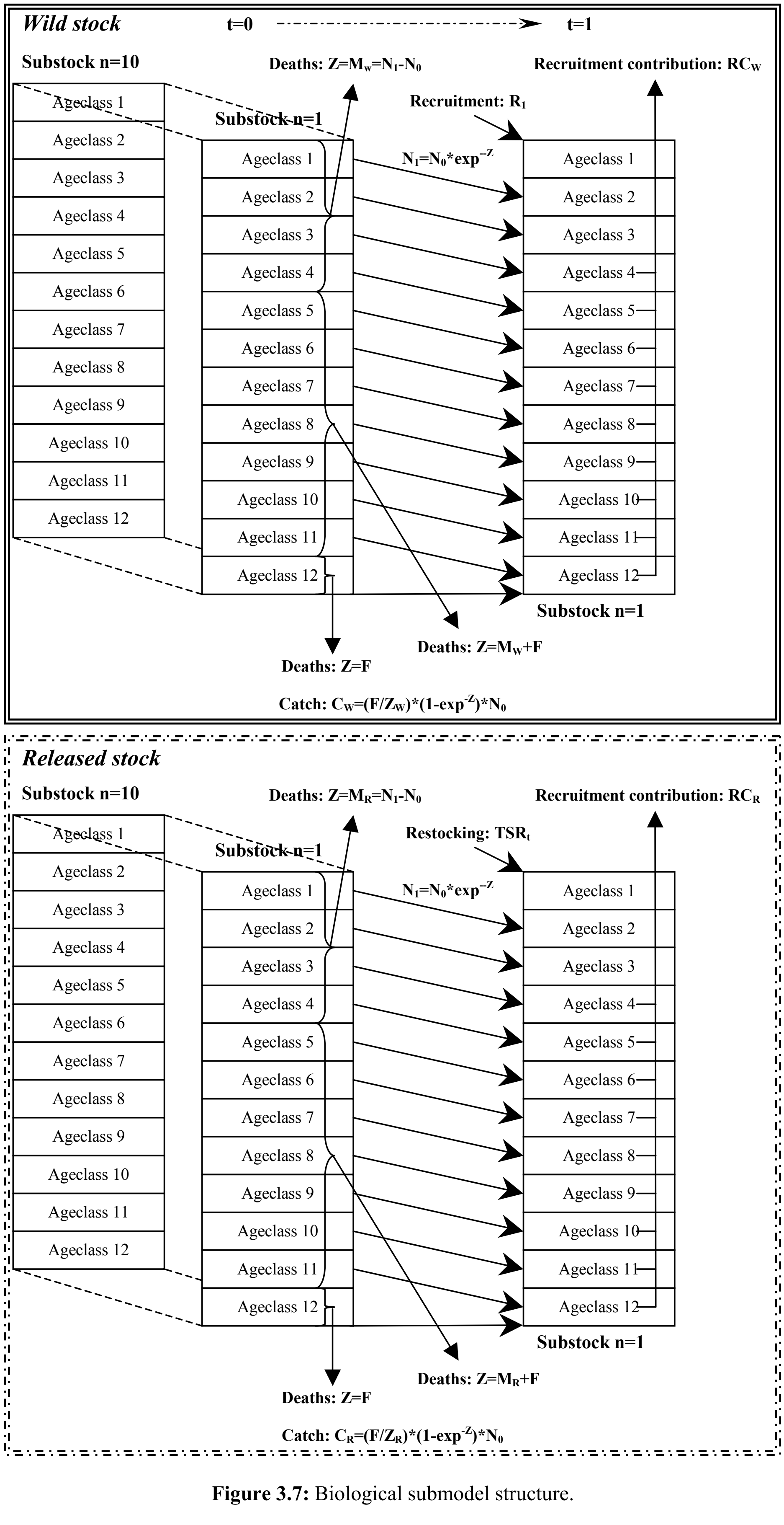


Figure 3.7: Biological submodel structure.

Wild and released components are age-structured stocks with negative exponential mortality (Eq.3.2), including the constant instantaneous rates of natural **(M)** and fishing mortality **(F)** (Eq.3.3) (Galluci *et al.*, 1996).

$$\mathbf{Z=-\ln S} \qquad \textbf{[1/year]} \qquad \textbf{[Equation 3.2]}$$

, where Z: instantaneous rate of total mortality [1/year], and S: survival fraction [%].

$$\mathbf{Z=M+F} \qquad \textbf{[1/year]} \qquad \textbf{[Equation 3.3]}$$

, where M: constant instantaneous rate of natural mortality [1/year], and F: constant instantaneous rate of fishing mortality [1/year].

Here, natural mortality is set to be constant; independent of the ageclass, from the first ageclass recruited into the fishery and is set at zero for individuals belonging to the last ageclass. Fishing mortality is zero for individuals under the minimum legal size (test diameter < 7,0 cm i.e. ageclasses <5), and thereafter applied for all individuals from the ageclass 5 onwards. Wild and released individuals have differential natural instantaneous mortality rates, but fishing mortality is constant for both stocks, being applied on an annual basis in accordance to the criteria described below.

Each stock (wild and released) could be distributed into up to ten sub-stocks, which are equally structured in twelve ageclasses calculated on an annual basis. Thus the population size **(N_t)** at a given age *t* (Galluci *et al.*, 1996) is given by (Eq. 3.4),

$$\mathbf{N_t=N_c*exp^{-Z(t-c)}} \qquad \textbf{[individuals/year]} \qquad \textbf{[Equation 3.4]}$$

, where N_c: abundance at an arbitrary initial time c [individuals] and Z: instantaneous rate of total mortality [1/year]

Commercial stock is integrated as the sum of individuals sized over the minimum legal size of the fishery (70 mm), and hence total catch **(C_t)** (Galluci *et al.*, 1996) is given by the instantaneous fishing mortality rate acting over this group on each stock (Eq. 3.5). The submodel assumes a constant fishing mortality for all commercially sized individuals, and considering a homogeneously distributed population; all the individuals have equal probability to be captured.

$$\mathbf{C_t=(F_t/Z_t)*(1-exp^{-Z}{}_t)*N_t} \qquad \textbf{[individuals/year]} \qquad \textbf{[Equation 3.5]}$$

, where F_t: constant instantaneous rate of fishing mortality at age t [1/year], Z: instantaneous rate of total mortality at age t [1/year], and N_t: abundance at age t [individuals].

Inputs into wild stock are represented by natural recruitment (Eq. 3.6). This consists of a given fixed batch of recruits, which is considered to be independent of the size of the parental stock and not affected by variations in fishing pressure. The submodel also assumes that natural recruitment into the fishery is in form of sharp- edge single shut pulse, and hence all recruits enter the fishery at the same time. Natural recruitment is generated either from outside and/or inside the system (coastal area) and is equally distributed into the 10 constituent wild sub-stocks, through the first ageclass of this stock.

$$\mathbf{N_t = N_c - D_c + R_c} \qquad \textbf{[individuals/year]} \qquad \textbf{[Equation 3.6]}$$

, where N_c: abundance at an arbitrary initial time c [individuals/year], D_c: total deaths at time c [individuals/year], and R_c: recruitment at time c [individuals/year].

Even though natural recruitment is not set to be auto-generated, an estimation of the potential contribution **(RC_t)** of the spawning stock present in the area to total recruitment into the system is calculated (Eq. 3.7).

$$\mathbf{RC_t = SS_t * SR * F * SI * PS} \qquad \textbf{[individuals/year]} \qquad \textbf{[Equation 3.7]}$$

, where SS_t: spawning stock at time t [individuals/year], SR: sex ratio [%], F: fecundity [larvae per individual], SI: settlement index [%], and PS: post-settlement survivorship [%]

When restocking is considered as a management approach, it takes effect through the introduction of hatchery- reared batches of juveniles, which are equally distributed into up to ten sub- stocks that form a virtual released stock. The overall magnitude of these batches (total seed released) is externally calculated using the production submodel. Additionally, the quantitative distribution between sub-stocks and geographic allocation among selected restocking areas is also externally determined, using the spatial submodel, which interacts directly with the GIS-based restocking model (GISRM).

For this stock, the submodel assumes that all individuals eventually released are the same age, therefore belong to the same cohort and will enter to the fishery at same time. Additionally, excepting for the natural mortality rate, these individuals are subjected to identical biological, environmental, fishing and management conditions as the wild stock inhabiting the costal lease. Accordingly the batch of hatchery- reared seed is released, and added on an annual basis into the released stock through the first ageclass.

3.4.3 THE PRODUCTION SUBMODEL

Given a production target in terms of total recruitment (defined as the level required to support the target catch), and the estimated recruitment level occurring in the area, the objective of this submodel was to assess the state of the recruitment level in the system. Based on the output, if the system shows a recruitment shortfall, this submodel quantifies the stocking contribution required to balance the system. Otherwise, it is assumed that the system is in balance, and therefore recruitment levels are sufficiently robust to support the harvest at the expected commercial level.

The production submodel structure is a simple (Fig. 3.8), but important intermediate linking element between socio-economic requirements, production targets and resource population management.

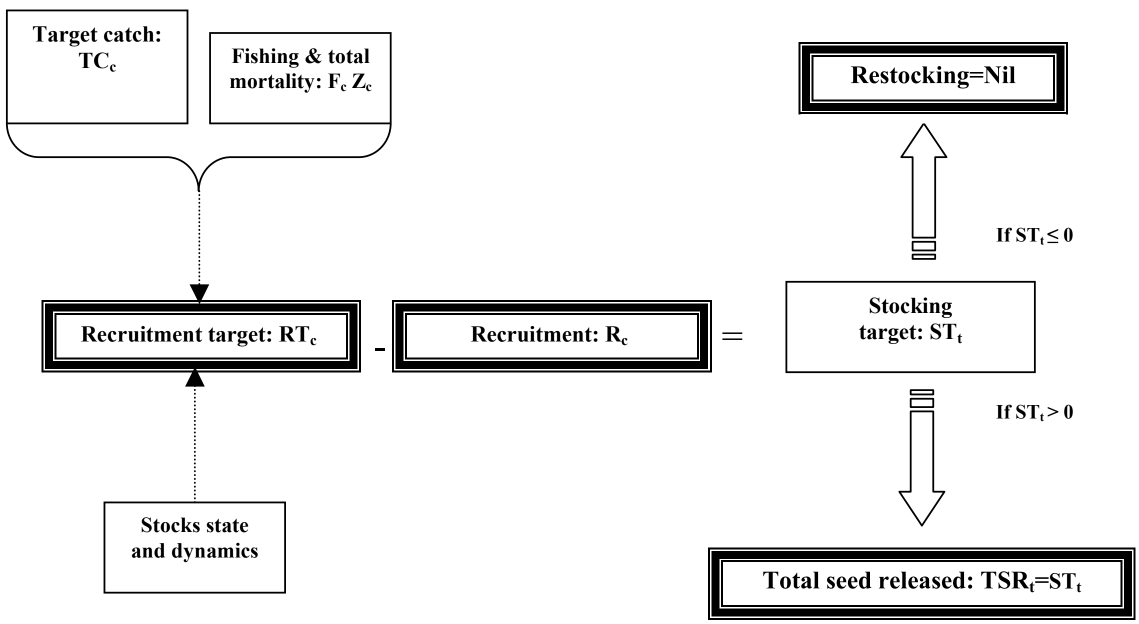


Figure 3.8: Production submodel structure.

Here, the recruitment target corresponds to the recruitment necessary to sustain a certain level of harvest to be defined by the user in terms of the target catch, which is externally estimated in the socio-economic submodel. Then, if the actual estimated recruitment at the area is smaller, the system is designed to make up for the shortfall in recruitment by stocking (stocking target). Accordingly, the stocking target **(ST_t)** is estimated by subtracting the user-defined recruitment target (**RT_c**) and the estimated recruitment (**R_c**) in the area (Eq. 3.8).

$$ST_t = RT_c - R_t \quad \text{[individuals/year]} \qquad \text{[Equation 3.8]}$$

, where RT_t: recruitment target at an arbitrary time c to support sustainable exploitation a given commercial level [individuals/year*study area], and R_t: actual recruitment in the area at time t [individuals/year*study area].

If this value is positive and restocking is selected, the total amount of seed to be released **(TSR_t)** per year is estimated to make the balance in the system, and therefore equal to the stocking target (**ST_t**) (Eq. 3.9). Otherwise, it is assumed that the system does not require external support to recruitment and the restocking contribution is nil.

$$TSR_t = ST_t \quad \text{[individuals/year]} \qquad \text{[Equation 3.9]}$$

, where ST_t: restocking target [individuals/year].

As previously pointed out, restocking is optional within the simulated system at any time. However, even when considered and enabled by the user, the dynamic system itself was designed to quantify its influence, magnitude, timing and distribution over the balance in the population. Thus, the software will provide a specific quantification for a restocking programme and its timing in order to keep as much as possible a balanced population

3.4.4 THE SOCIO- ECONOMIC SUBMODEL

The socio- economic submodel (Fig. 3.9) primarily aimed to provide a quantitative measure of social and economic requirements of the fishing community. This data was considered to be the major starting point for dimensioning specific commercial targets for this benthic resource in a given small-scale fishery. It was therefore essential information that defined the objective for the design and evaluation of the exploitation and management plan. Secondly, as a feedback this submodel attempted to develop formal dynamic financial evaluation of the project, allowing the user to study and analyse the economic consequences of different management and exploitation scenarios. To do so the system was modelled as the basis of major investments, operational costs, and incomes; and project profitability determined by traditional discounted cash flow-based methodologies.

Economic factors were dynamically linked to stock dynamics, and separately calculated for both components- wild and released stock. This estimation was based on each stock proportional contribution **(PSC_t)** (e.g. wild stock contribution **(WSC_t)**: released stock contribution **(RSC_t)**=0.6:0.4) into the total population (Eq. 3.10). Subsequently, these two components were integrated on a whole population basis to develop the final costs, incomes, payment (cash flow) and net present value calculations.

$$PSC_t \Leftarrow\Rightarrow WSC_t = Nw_t/N_t \quad \wedge \quad WRC_t = NR_t/N_t \quad [\%] \qquad \text{[Equation 3.10]}$$

, where Nw_t: wild stock population at time t [individuals/year], and N_t: total population at time t [individuals/year]

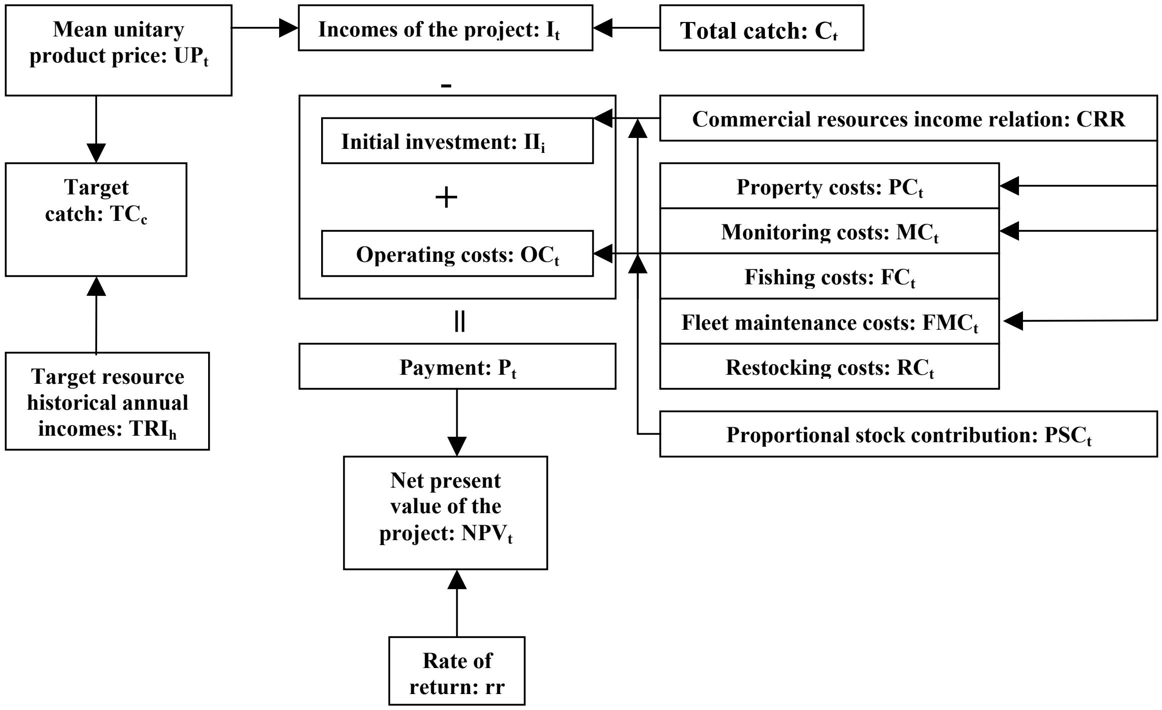


Figure 3.9: Socio- economic submodel structure

When required, economic functions were built up on the basis of target resource specific base, e.g.: specific investment in fishing fleet associated to the fishery of the red sea urchin. This was estimated by calculating the specific target resource incomes contribution to the overall commercial resources incomes, multiplying this by the elements shared between commercial resources. The relation of income between commercial resources **(CRR)** (Eq. 3.11) was defined considering the historical captures and average market prices for the calculation of total and specific- resource gross income.

$$\mathbf{CRR = TRI_h / CRI_h \quad [\%]} \qquad \textbf{[Equation 3.11]}$$

, where TRI_h: target resource historical annual incomes at a previous time h [$/year], and CRI_h: total historical annual incomes from all commercial resources in the cove at a previous time h [$/year].

Considering the social reference of the expected annual incomes produced from the fishery and taking into account the mean unitary price of the product, plus a safety margin factor, the final productive objective of the project ('target catch' **(TC_c)**) was determined (Eq. 3.12). The target catch factor can be used to scale-up the catch target of the system, as a way to ensure that having fulfilled the commercial requirements ('target catch'), a residual commercial stock will remain in the system. This represents a fundamental index the user may use as reference to estimate the minimum recruitment (recruitment target) required to return this level of harvest.

$$TC_c=(TRI_h/UP_t)*TCF \qquad \text{[individuals/year]} \qquad \text{[Equation 3.12]}$$

, where TRI: target resource historical annual incomes at a previous time h [$/year], UP_t: mean unitary price of the product at time t [$/individual], and TCF: target catch factor [times].

Investments within the project were treated as a separate element from the operational costs and were determined by the initial investment in the fishing fleet (Eq. 3.13). This was based on the normal fishing fleet operating at the cove and the investment required on a boat, out- board motor, air-compressor, and diving equipment. As a shared element between commercially exploited resources, it was calculated on a resource specific basis, hence taking into account the relation of income between commercial resources previously estimated. Furthermore, initial investment **(II_i)** would take place during year 0 and by including maintenance within operational costs it was expected that no major re-investment would be considered.

$$II_i=FF*CRR*UFI \qquad \text{[\$/year 0]} \qquad \text{[Equation 3.13]}$$

, where FF: fishing fleet [fishing units], CRR: relation of income between commercial resources [%], and UFI: unitary fleet investment [$/fishing unit].

Operating costs **(OC_t)** of the project are divided into 5 major categories- property, monitoring, restocking, fleet maintenance and fishing costs. Here, restocking and fishing cost components are defined as variable, while, property, monitoring and fleet maintenance cost components are assumed to be fixed. The overall sum of these elements, based as the contribution of wild and released stocks, represents the total operational costs of the project (Eq. 3.14).

$$OC_t=(PC_t+MC_t+FC_t+FMC_t+RC_t)*PSC_t \qquad \text{[\$/year]} \qquad \text{[Equation 3.14]}$$

, where PC_t= property costs at time t [$/year], MC_t: monitoring costs at time t [$/year], FC_t: fishing costs at time t [$/year], FMC_t: fleet maintenance costs at time t [$/year], RC_t: restocking costs at time t [$/year], and PSC_t: proportional stock contribution at time t [%].

Property costs **(PC_t)** are calculated as a function of the size of the area and the unit tax rate for the lease (Eq. 3.15). In accordance to current AMEBR regulations, the fishermen' s association must pay the state on an annual basis per hectare of fishing ground, for the use and exploitation of the benthic resources considered on the management plan. Being a shared operational cost, this element is also estimated on a resource contribution basis, and also separated for both wild and released stock populations.

$$PC_t=MA*UT*PSC_t*CRR \quad [\$/year] \qquad \textbf{[Equation 3.15]}$$

, where MA: size of management area [ha], UT: AMEBR unitary tax rate [$/ha*year], PSC_t: proportional stock contribution at time t [%], and CRR: relation of income between commercial resources [%].

Monitoring costs **(MC_t)** are represented by a given technical assistance cost, and an operational monitoring cost, associated with the development of a field- based resource evaluation programme. The operational monitoring cost is defined by the fishing opportunity cost of the supporting fleet undertaking the field sampling. Both components are functions of the size of the study area and the desired number of monitoring sessions to be held during the year (Eq. 3.16).

$$MC_t=(AC+FOC*MF)*MA*MS*PSC_t*CRR \quad [\$/year] \qquad \textbf{[Equation 3.16]}$$

, where AC: technical assistance cost [$/ha*day], FOC: fishing opportunity cost [$/fishing unit*day], MF: monitoring fleet [fishing units/ha], MA: size of management area [ha], MS: monitoring sessions [days/year], PSC_t: proportional stock contribution at time t [%], and CRR: relation of income between commercial resources [%].

Since restocking costs **(RC_t)** are strictly related to the released population, there is no wild population component in this cost element (Eq. 3.17). The temporal variability of these costs relies mainly on the amount of seed released into the system. The model assumes a land- based restocking technique, using pre- selected intertidal pools with the participation of a fishermen labour group, and a supporting fleet if required. Taking into account a given restocking rate, the total seed to be released and restocking events determines the working team required **(RT)** during the seeding process, and therefore labour and the fishing opportunity cost of the supporting fleet associated with the exercise (Eq. 3.18). In addition to this, restocking costs may also vary with the unit price of the seed introduced.

$$RC_t=(TSR_t*SP)+(RT_t*UL*E_t)+(FOC*SF*E_t) \quad [\$/year] \qquad \textbf{[Equation 3.17]}$$

, where: TSR_t: total amount of seed to be released at time t [individuals/year], SP: unit seed price [$/individual], RT: required restocking team at time t [labor units], UL: unit restocking labor cost [$/labor units*day], E_t: restocking events at time t [days/year], FOC: fishing opportunity cost [$/fishing unit*day], and SF: supporting fleet [fishing units].

$$RT=TSR_t/(E_t*RR) \quad [labor\ units] \qquad \textbf{[Equation 3.18]}$$

, where TSR_t: total amount of seed to be released at time t [individuals/year], E_t: restocking events at time t [days/year], and RR: restocking rate [seeds/labor unit*day]

Fishing costs **(FC_t)** are determined by the number of fishing sessions required **(RFS_t)** to capture the total estimated catch, assuming that the total fishing fleet operates under normal conditions on a daily fixed unit fishing cost regimen (Eq. 3.19). As the number of fishing sessions is a function of the total catch, this is calculated on the basis of a fixed, but changeable, daily average catch rate (Eq. 3.20).

FC_t=FF*RFS_t*UFC [$/year] [Equation 3.19]

, where FF: fishing fleet [fishing units], RFS_t: required fishing sessions at time t [days/year], and UFC: unit fishing cost [$/fishing unit*day]

RFS_t=C_t/(CR*FF) [days/year] [Equation 3.20]

, where C_t: total catch at time t [individuals/year], CR: average catch rate [individuals/fishing unit*day], and FF: fishing fleet [fishing units].

Fleet maintenance costs **(FMC_t)** are related to the small but regular expenses on fishing gear, motor and general equipment repairs and replacements (Eq. 3.21).

FMC_t=FF*UMC*m*PSC_t*CRR [$/year] [Equation 3.21]

FF: fishing fleet [fishing units], UMC: unit fleet maintenance cost [$/fishing unit*month], m: 12 [months/year], PSC_t: proportional stock contribution at time t [%], and CRR: relation of income between commercial resources [%].

Incomes of the project **(I_t)** are calculated as a function of the annual catch and the price of the product (Eq. 3.22). The last may vary depending on the market preferences and conditions. In this model it is assumed that the price can have two different values at the same time depending on the calibre or standard of the product (test diameter), which the user can define according to the international and national market preferences. Likewise, these prices may also vary with time depending on market conditions.

I_t=C_t*UP [$/year] [Equation 3.22]

, where C_t: total catch at time t [individuals/year], and UP: unit price product destined for national and international markets [$/individual].

The payment **(P_t)** (Eq. 3.23) and the net present value **(NPV_t)** of the project are calculated on the basis of discounted cash flow (Eq. 3.24), for which interest rate is a user- defined input. When interest rate is constant, the net present value used to evaluate the desirability of investments can be defined as follows.

P_t=I_t-OC_t [$/year] [Equation 3.23]

, where I_t: Incomes of the project at time t [$/year], II_i: initial investment of the project at an initial time 0 [$/year 0], and OC_t: Operating costs of the project at time t [$/year].

NPV_t=P_0+(P_1/(1+rr))+ (P_2/$(1+rr)^2$)+…+ (P_t/$(1+rr)^t$) [$/year] [Equation 3.24]

, where P_0: initial investment (II_i) of the project at an initial time 0 [$/year 0], P_t: payment of the project at time t [$/year], and rr: rate of return expected for the project [%].

3.4.5 THE SPATIAL SUBMODEL

This submodel (Fig 3.10) was constructed to process essential input data regarding the suitability of restocking sub- areas, and their availability and extension within the area of management, externally provided by the GIS restocking model (Chapter 4). As a feedback the submodel attempted to make a quantitative measure of the allocation of individuals, and subsequently the surface coverage process of these zones as successive restocking exercises take place.

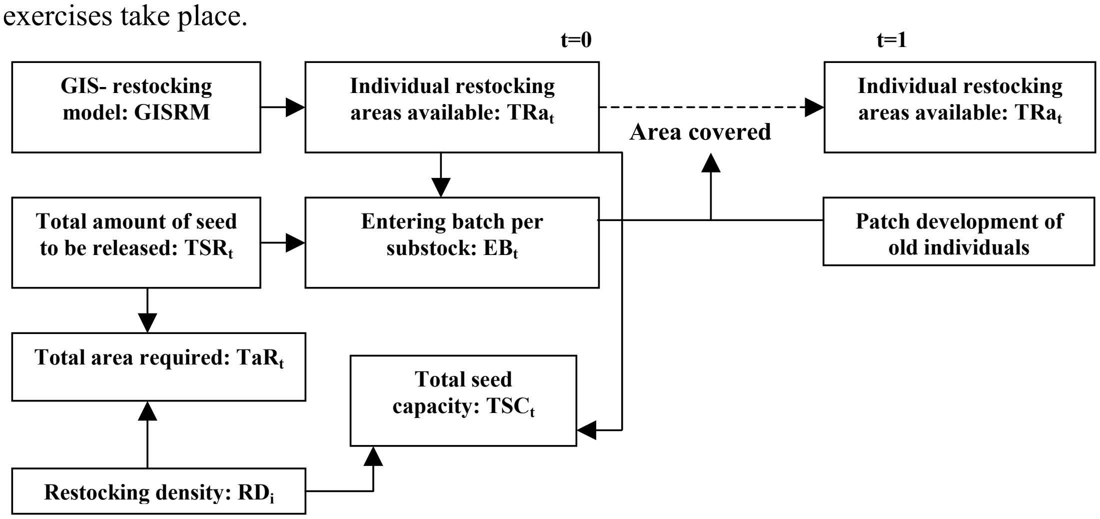


Figure 3.10: Spatial submodel structure.

Thus, total seed released is proportionally distributed in accordance to the relative contribution of the restocking sub- areas, allowing differential allocation of individuals forming the released stock population (Eq. 3.25). Thus, each and every entering batch **(EB_t)** per substock is supposedly allocated in a different restocking sub- area.

$$\mathbf{EB_t = TSR_t * RSaC_t} \quad \textbf{[individuals/year]} \qquad \textbf{[Equation 3.25]}$$

, where TSR_t: total amount of seed to be released at time t [individuals/year], and $RSaC_t$: individual restocking sub-area contribution to total restocking area at time t [%].

As restocking exercises are performed, restocking sub- areas are allocated and covered as function of the new individuals introduced into the system and the old individuals surviving and growing (patch development), reducing the overall effective substrate available, and therefore individual restocking areas available (**TRa_t)** are calculated (Eq. 3.26).

$$\mathbf{TRa_t = TRa_i - [EB_t/RD_i + ((RN_t - EB_t)/RD_t - ((RN_t - EB_t)/RD_i))]} \quad \mathbf{[m^2]} \qquad \textbf{[Equation 3.26]}$$

, where TRa_i: total restocking area available at an initial time i [m^2], EB_t**:** entering batch per substock at time t [individuals/year], RD_t: restocking density at time t [individuals/m^2], calculated as the initial density minus the proportional annual density reduction [%/year], RN_t: total restocked population in a substock at time t [individuals/year], and RD_i: restocking density at an initial time i [individuals/m^2].

Based upon the optimal initial restocking density this submodel allows the estimation of the total area required **(TaR_t)** for the seed to be released (Eq. 3.27).

$$TaR_t = TSR_t/RD_i \qquad [m^2/year] \qquad \textbf{[Equation 3.27]}$$

, where TSR_t: total amount of seed to be released at time t [individuals/year], and RD_i: restocking density at an initial time i [individuals/m^2].

Finally, the spatial submodel also calculates the overall seed capacity **(TSC_t)** of the system, taking into account the selected sub- areas available for restocking (Eq. 3.28).

$$TSC_t = TRa_t * RD_t \qquad \textbf{[Equation 3.28]}$$

, where TRa_i: total restocking area available at a time t [m^2], and RD_i: restocking density at a time t[individuals/m^2].

3.4.6 MODEL INPUTS

Inputs required for running the bio-socio-economic simulation model are aggregated into five separate windows: Inputs 1 to 5.

On windows 1 and 2,'Biological inputs (1-2)' (Fig. 3.11) correspond to the complete age distribution of the wild stock in the study area. Here the user is allowed to include up to ten substocks, distributed in 12 ageclasses each. This data is essential to run the BSESM, and therefore has to be entered in. Size thresholds for each ageclass were calculated on the basis of the LVF growth equation (Table A.1, Appendix 1).

As wild stock size distribution data can be extracted from the resource assessment on the base line study, the user must re-arrange this data in terms of ages for input into the software. Thereafter, as resource monitoring takes place, the user may easily update this information in the simulation model, and re-run multiple macro-scenarios with the updated age distribution of the wild population.

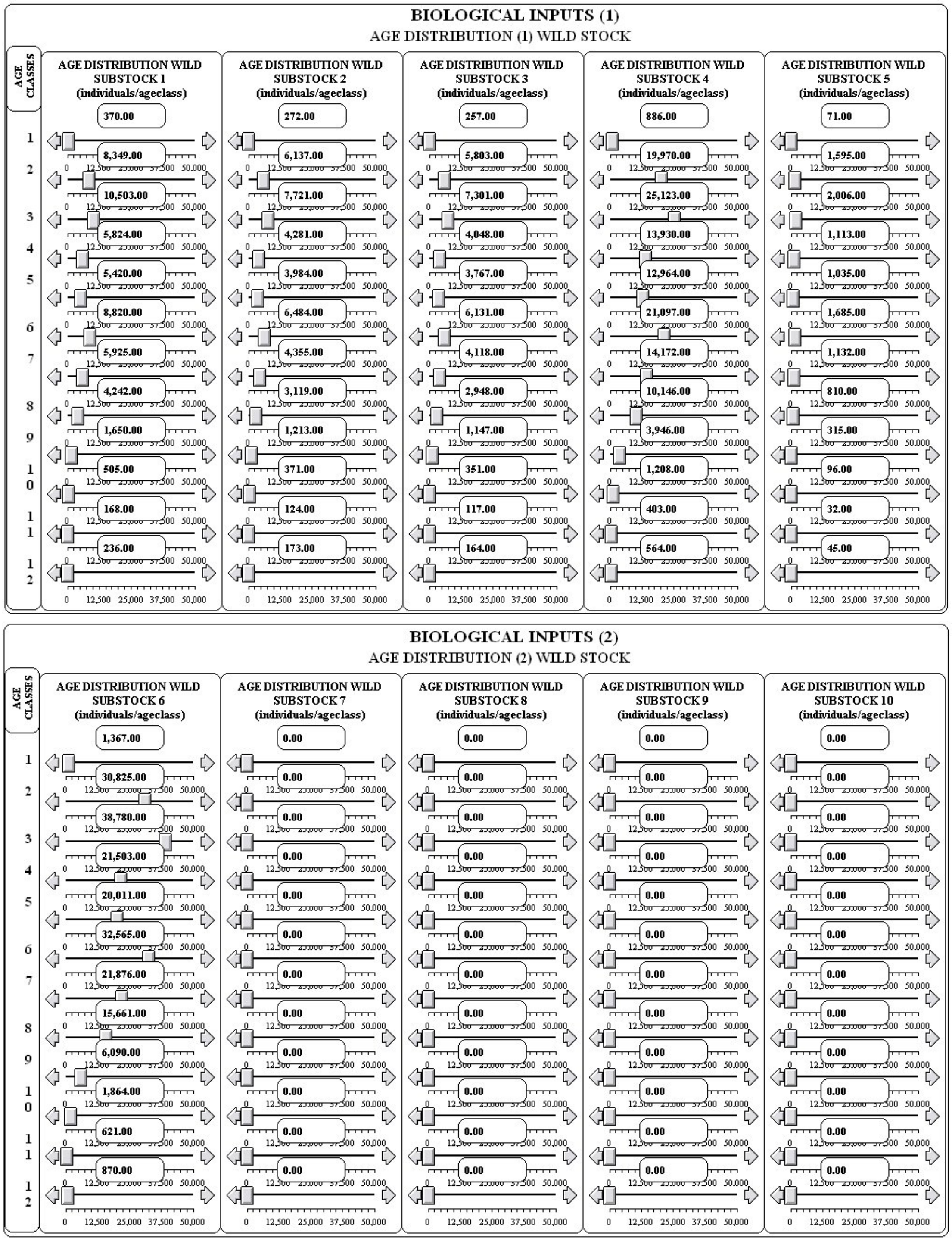


Figure 3.11: Input windows 1 and 2.

Under ‘Biological, fishery and monitoring inputs’, window 3 (Fig. 3.12) integrates a number of mortality, population structure, reproduction, fishing and monitoring inputs. Here, all the inputs must be entered, except for the reproduction parameters (saving ‘total natural recruitment’), which may be left with a cero value, if the estimation of ‘natural recruitment contribution in the system’ is not needed.

Under ‘population structure’ parameters is described the ‘target catch factor’, which may be optionally used to scale-up the commercial target of the system, in a way to ensure that the minimum commercial requirements are fulfilled within the management plan. Thus, if according to the socio-economic requirements, the ‘target catch’ is calculated at 125,000 individuals per year and the factor is 1,5, then the final target setting for the system will be 187,500 sea urchins (125,000*1,5).

Here, the user must initially estimate the ‘recruitment target’ either running the model manually on Constructor or optimizing the ‘total natural recruitment’ input parameter using Solver, so as to estimate the recruitment level required to sustain the 'target catch' of the system.

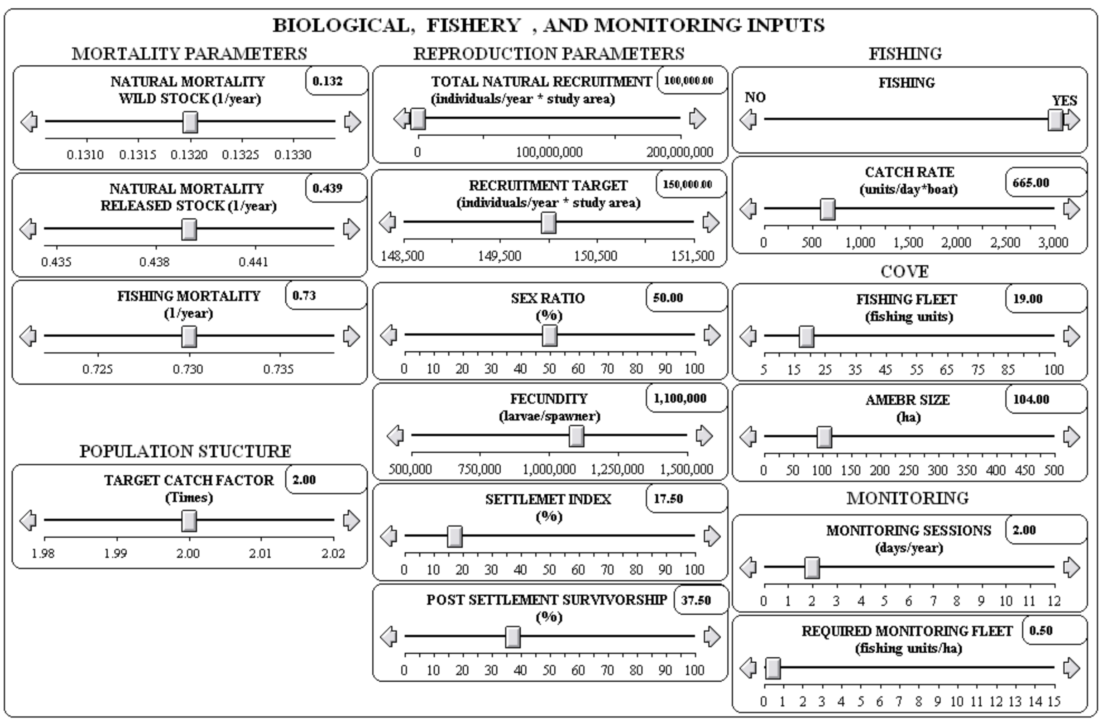


Figure 3.12: Input window 3.

Input window 4 (‘Socio-economic and productive inputs’) (Fig. 3.13), consists of the various elements involved on the socio-economic structure of the project, such as the capital investment, operating costs, historical total-resources and specific-resource incomes at the cove, product prices, and the interest rate set for the project. Here, restocking-related costs must only be fulfilled if restocking is considered within the management plan of the fishery.

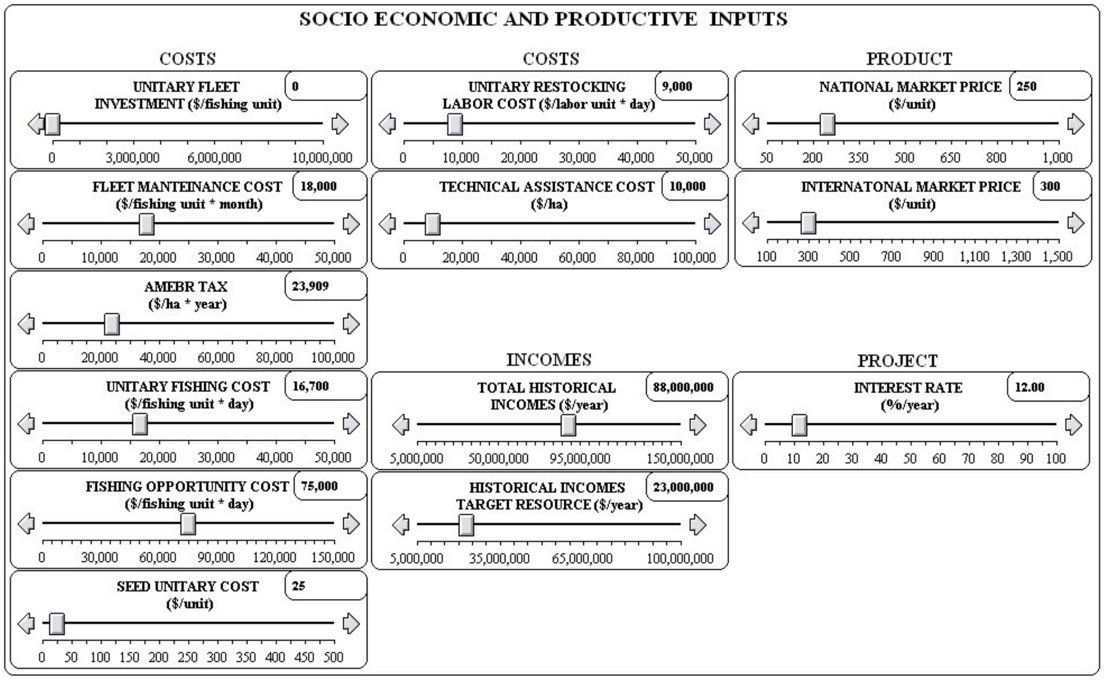


Figure 3.13: Input window 4

Finally, window 5 ('Restocking inputs') (Fig. 3.14) integrates all required data for setting up the restocking exercise, This window includes the user-control button for inclusion or exclusion of restocking in the system, which may be switched on/off at any time. However, if restocking is enabled all relevant input parameters and data must be entered so that the software can operate properly and estimate related outputs.

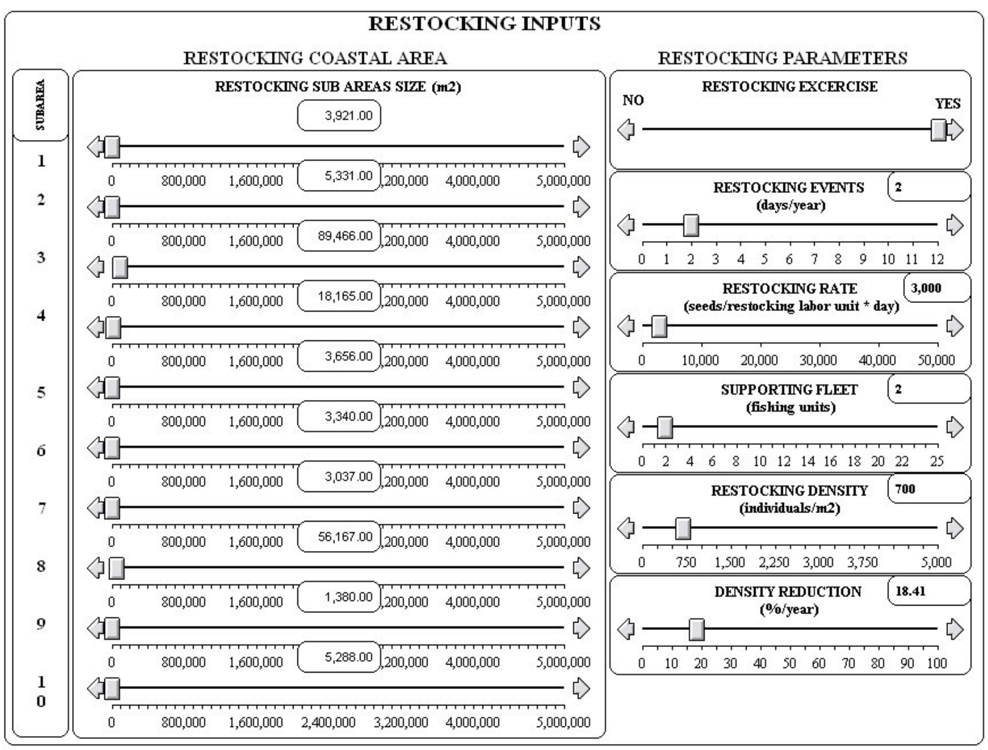


Figure 3.14: Input window 5

Table 3.7 lists all input data required, including the full identification and window location, corresponding units and general description of each and every parameter.

Table 3.7: Input parameters required for running the BSESM.

Input window 1 & 2	**Input parameter**	**Units**	**General description**
Ageclass distribution of the wild stock	(12) Ageclasses abundance of (10) wild substocks	individuals/ageclass	Number of individuals within each ageclass in up to ten substocks forming the wild stock
Input window 3			
Mortality parameters	Natural mortality wild individuals Natural mortality released individuals	1/year	Instantaneous natural mortality rate of wild and stocked individuals in their natural environment
	Fishing mortality	1/year	Instantaneous fishing mortality rate over the commercial stock of both stock components
Population structure	Target catch factor	Times	Safety index used to ensure the expected size of the exploitable fraction in the final population
Reproduction parameters	Total natural recruitment	individuals/year*study area	Total effective natural recruitment taking place in the zone
	Recruitment target	individuals/year*study area	Total natural recruitment necessary to sustain a certain level of harvest in the system
"	Sex ratio	%	Proportion between males and females in the population
"	Fecundity	larvae/spawner	Expected fecundity for a sexually mature adult individual
"	Settlement index	%	Percentage of individuals settling and metamorphosing
"	Post settlement survivorship	%	Percentage of individuals surviving after metamorphosis
Fishing	Fishing	Yes/no	Inclusion or exclusion of exploitation within the management plan
"	Catch rate	units/ day * boat	Daily average capture per fishing unit at normal fishing activities operating at the zone
Cove	Fishing fleet	fishing units	Number of fishing boats constituting the normal fleet operating at the cove
"	AMEBR size	Ha	Size of the area of management and exploitation leased to the fishermen association
Monitoring	Monitoring sessions	days/year	Number of resource evaluation programmes to be held at the area during the year
"	Required monitoring fleet	fishing units/ ha	Minimum fleet required to undertake resource evaluation programme and sampling

Cont. **Table 3.7.**

Input window 4	Input parameter	Units	General description
Costs	Unit fleet investment	$/fishing unit	Unitary cost per boat, out- board motor, air-compressor, diving equipment and fishing gear in general
"	Fleet maintenance cost	$/fishing unit*month	Monthly maintenance expense per fishing boat
"	AMEBR tax	$/ha*year	Legal tax to pay for the lease on a annual basis
"	Unitary fishing cost	$/fishing unit*day	Average operational fishing cost during a normal fishing session estimated on a daily basis per fishing boat
"	Fishing opportunity cost	$/fishing unit* day	Amount of incomes that could be obtained on a daily basis if fishing activities are performed
"	Seed unit cost	$/unit	Market price for a hatchery- reared juvenile individual (size≈2 cm test diameter)
"	Unit restocking labour cost	$/labour unit*day	Operational cost of non- qualified labor force used during the seeding process
"	Technical assistance cost	$/ha	Qualified technical assistance cost required for design, implementation, development and report of monitoring programmes
Incomes	Total historical incomes	$/year	Overall gross incomes traditionally generated from the sum of commercial resources at the cove
"	Historical incomes target resource	$/year	Gross incomes historically obtained from the specific resource fishery at the cove
Product	National market price	$/unit	Wholesale price offered at the beach for the catch destined to local or national market
"	International market price	$/unit	Wholesale price offered at the beach for the catch destined to exportation or international markets
Project "	Interest rate	%/year	Internal rate of return expected from the project
Input window 5			
Restocking zone 1 to 10	Sub-area size (10)	m^2	Effective area available for restocking within each restocking sub- area selected
Restocking parameters	Restocking	Yes-no	Inclusion or exclusion of restocking exercises within the management plan
"	Restocking events	days/year	Number of restocking sessions to be held during a given restocking exercise
"	Restocking rate	seeds/restocking labour unit * day	Number of individuals
	Supporting fleet	fishing units	Fishing fleet supporting the restocking exercise
	Restocking density	individuals/m2	Initial restocking density
	Density reduction	%/year	Annual average reduction on natural density of individuals as they grow forming patches

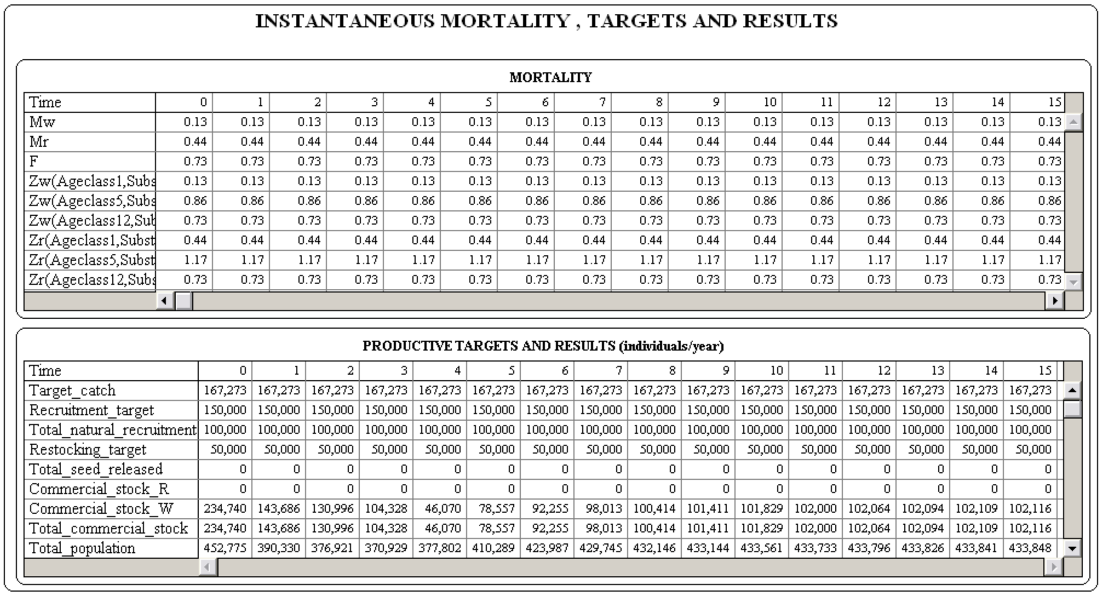
3.4.7 MODEL OUTPUTS

Once the model is begun, three different output are displayed- time-series tables, value boxes, time-series graphs and histograms. These displays are contained in eight separate windows- Outputs 1 to 8 (Table 3.8), and are continuously updated on a constant time-step basis as the model runs. These outputs can also be visualized and printed at any time during the simulation process.

Table 3.8: Outputs generated from for running the BSESM.

Output window 1	Results description	Display type	Units
Mortality	Annual natural (M) and fishing (F) constant instantaneous mortality rates plus total (Z) estimated mortality per ageclass	Time series table (1)	1/year
Productive targets and results	Target catch and total commercial stock; target population and total population, restocking target; commercial stock wild and released components	Time series table (1)	individuals/year
Output window 2			
Wild substocks dynamics	Dynamic age-distribution of (10) wild substocks and estimation of total population, spawning stock, commercial stock, natural recruitment contribution, natural recruitment per substock and catch.	Dynamic histogram (10) Value boxes (6)	individuals/year
Output window 3			
Released substocks dynamics	Dynamic age-distribution of (10) wild substocks and estimation of total population, spawning stock, commercial stock, natural recruitment contribution, natural recruitment per substock, total seed released and catch.	Dynamic histogram (10) Value boxes (7)	individuals/year
Output window 4			
Stocks dynamics	Wild and released stocks dynamics, including total population, total spawning stock, natural recruitment, commercial stock, total catch and total seed released.	Time-series line graph (2)	individuals/year
Output window 5			
Population dynamics	Total population dynamics, including total population, total spawning stock, recruitment target, total natural recruitment, total seed released, total commercial stock, target catch, and total catch.	time-series line graph (2)	individuals/year
Output window 6			
Restocking areas dynamics	Total seed capacity per sub- area, restocking area requirements per year and restocking area coverage process.	Time series table and dynamic histogram	units/sub- area m^2
Output window 7			
Economic evaluation of the project	Wild and released stocks specific investments, costs, incomes, payment and net present value of the project.	Time series table (4)	\$/year
Output window 8			
Cash flow curve	Total initial investment, total costs, total incomes, total payment and total net present value	Time-series line graph (2)	\$/year

Output window 1 (Fig. 3.15) shows time-series tables for the constant natural and fishing mortality, and the total instantaneous mortality rate set for the first (equal to the second-fourth ageclass), the fifth (equal to the sixth-eleventh ageclass) and the twelve ageclass, separately estimated for the wild and the released stocks. In addition to this, this window illustrates a time-series table summarizing the production targets and simulated results of the system including the: ‘target catch’, ‘recruitment target’, ‘total natural recruitment’, ‘restocking target’, ‘total seed released’, the commercial stock fractions of the wild and releases stock and the ‘total population’.



INSTANTANEOUS MORTALITY , TARGETS AND RESULTS

MORTALITY

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mw	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Mr	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
F	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Zw(Ageclass1,Subs	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Zw(Ageclass5,Subs	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Zw(Ageclass12,Sub	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Zr(Ageclass1,Subst	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Zr(Ageclass5,Subst	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
Zr(Ageclass12,Subs	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73

PRODUCTIVE TARGETS AND RESULTS (individuals/year)

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000
Total_natural_recruitment	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Restocking_target	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Total_seed_released	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	78,557	92,255	98,013	100,414	101,411	101,829	102,000	102,064	102,094	102,109	102,116
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	78,557	92,255	98,013	100,414	101,411	101,829	102,000	102,064	102,094	102,109	102,116
Total_population	452,775	390,330	376,921	370,929	377,802	410,289	423,987	429,745	432,146	433,144	433,561	433,733	433,796	433,826	433,841	433,848

Figure 3.15: Output window 1.

Output windows 2 and 3 (Fig. 3.16 and 3.17) present an annual dynamic histogram containing the age-distribution of all individual substocks integrating the wild and the released population component. Moreover, these windows include an annual estimate for a range of stock fractions, such as: the 'total population', the 'spawning stock', the 'commercial stock', the 'catch', the 'natural recruitment per substock', the 'natural recruitment contribution', and the 'released seed', if restocking was considered.

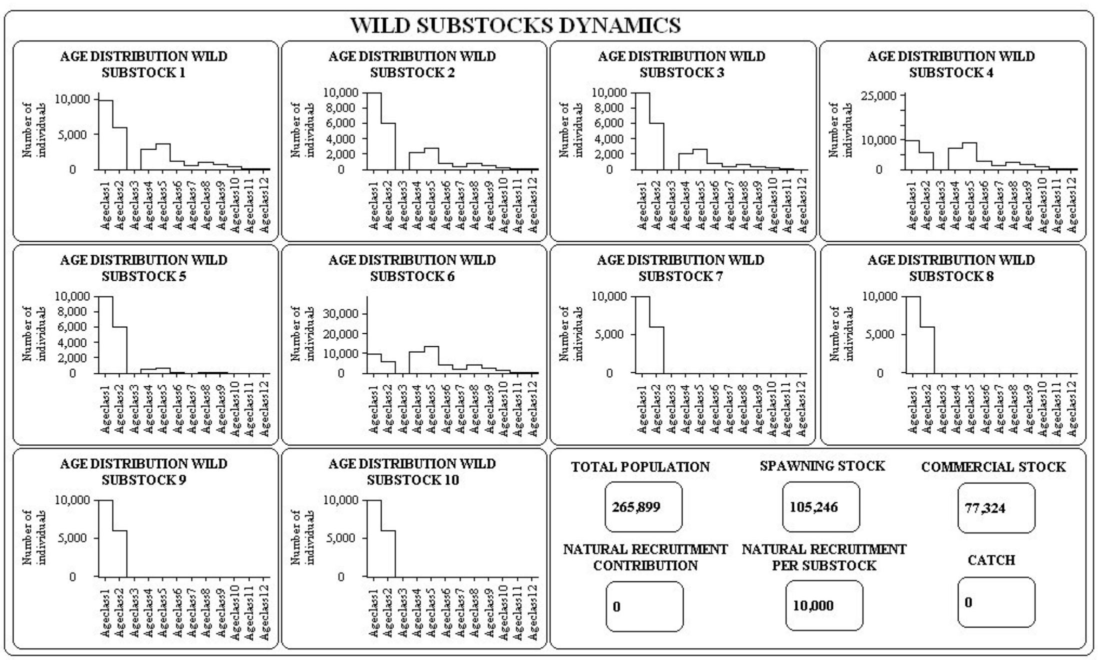


Figure 3.16: Output window 2.

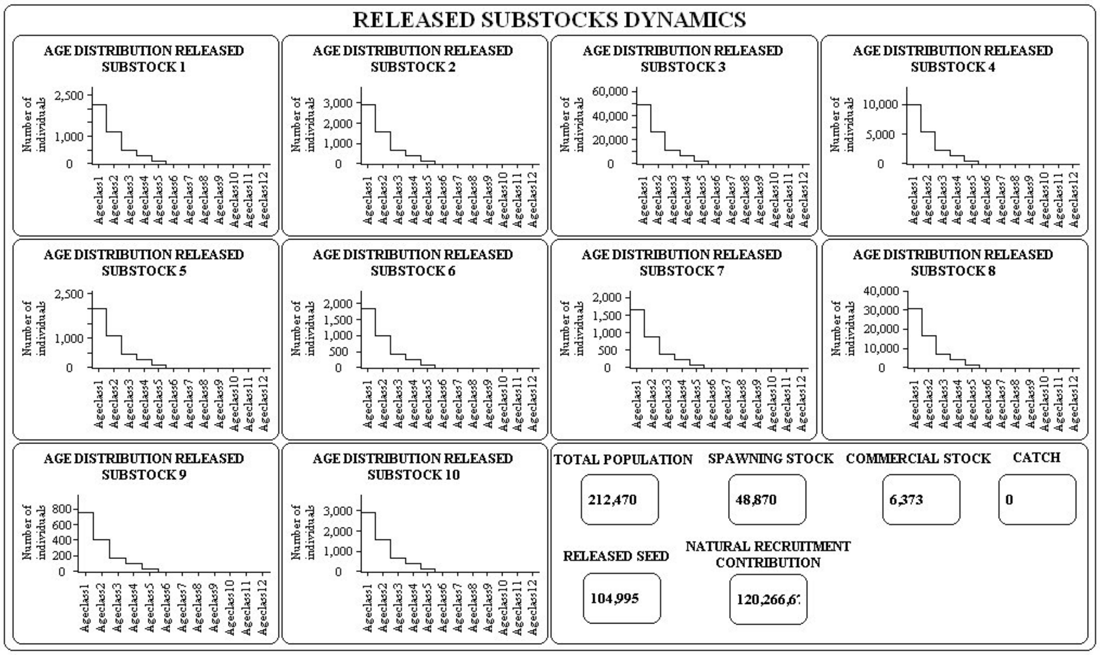


Figure 3.17: Output window 3.

Output window 4 (3.18) describes the time-series curves for the stock dynamics, separately estimated for wild and released components, including the same stock fractions previously mentioned.

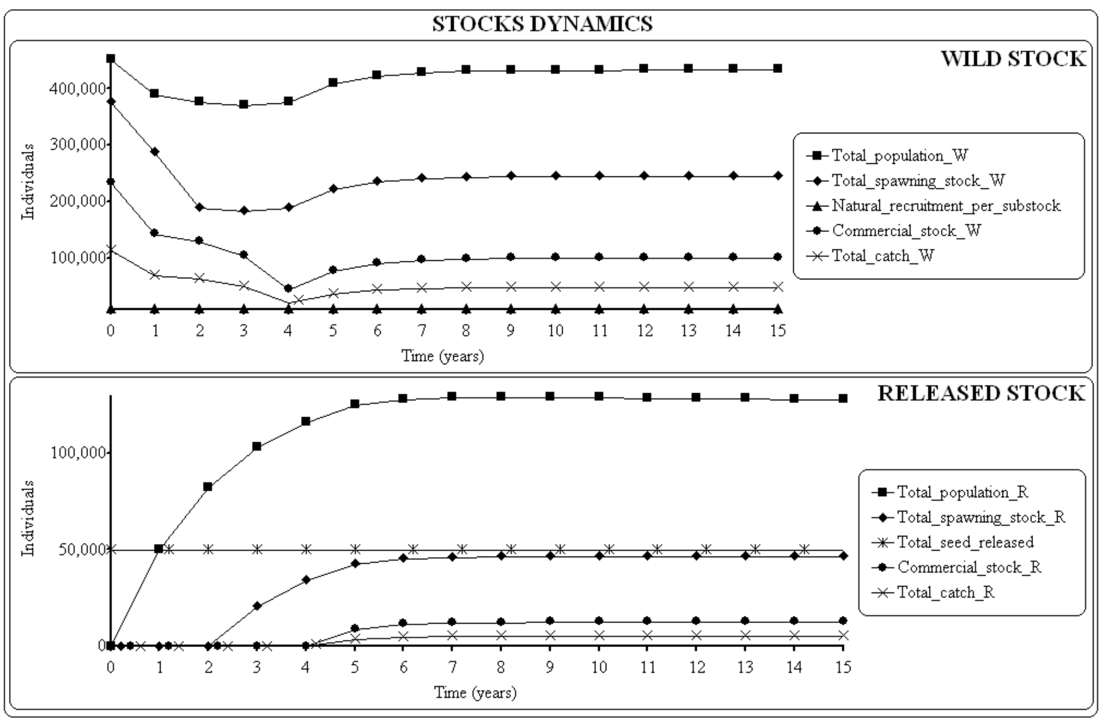


Figure 3.18: Output window 4

In a similar way, output window 5 (3.19) illustrates the time-series curves, but for the whole population dynamics and its fractions over the years plus the major targets of the system.

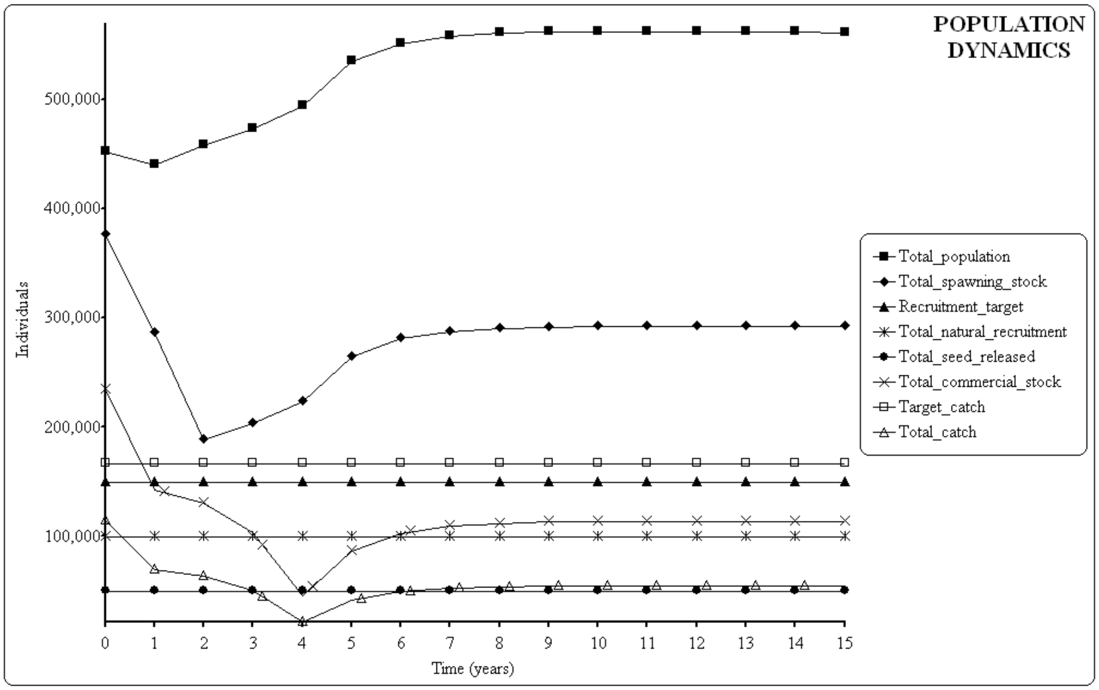
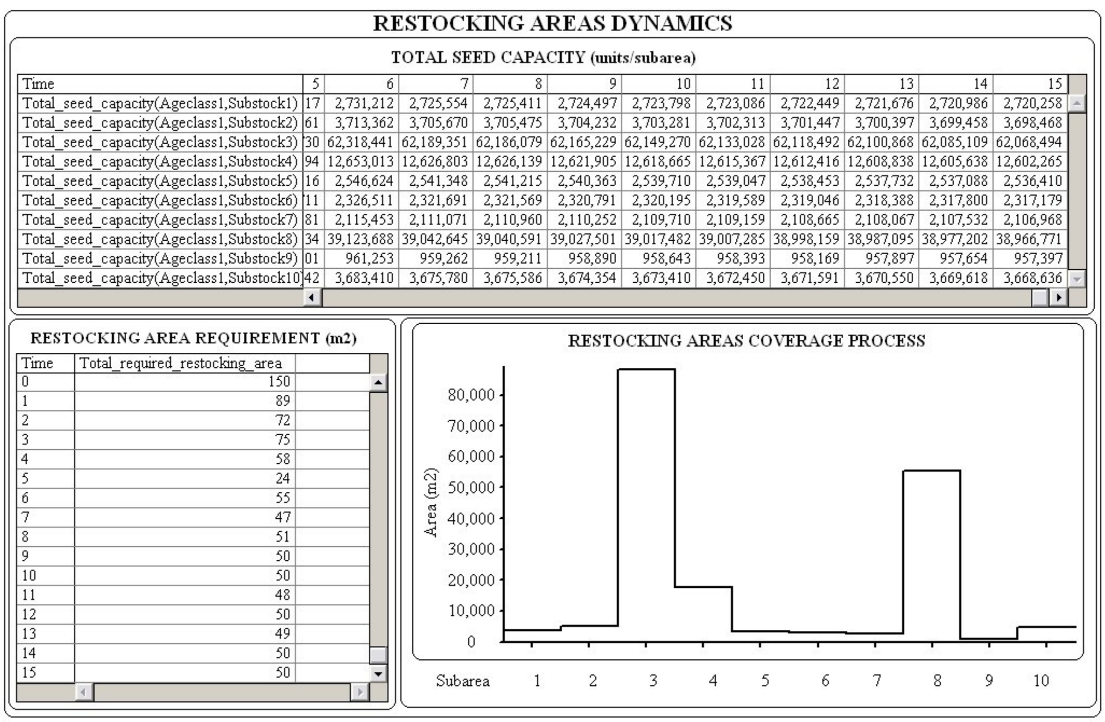


Figure 3.19: Output window 5

Output window 6 (Fig. 3.20) shows the spatial dynamics of the restocking areas, including a time-series table with the 'restocking area requirements', the estimated 'seed capacity' of each restocking site, and a dynamic histogram illustrating the 'restocking areas coverage process' within restocked sites.



RESTOCKING AREAS DYNAMICS

TOTAL SEED CAPACITY (units/subarea)

Time	5	6	7	8	9	10	11	12	13	14	15
Total_seed_capacity(Ageclass1,Substock1)	17	2,731,212	2,725,554	2,725,411	2,724,497	2,723,798	2,723,086	2,722,449	2,721,676	2,720,986	2,720,258
Total_seed_capacity(Ageclass1,Substock2)	61	3,713,362	3,705,670	3,705,475	3,704,232	3,703,281	3,702,313	3,701,447	3,700,397	3,699,458	3,698,468
Total_seed_capacity(Ageclass1,Substock3)	30	62,318,441	62,189,351	62,186,079	62,165,229	62,149,270	62,133,028	62,118,492	62,100,868	62,085,109	62,068,494
Total_seed_capacity(Ageclass1,Substock4)	94	12,653,013	12,626,803	12,626,139	12,621,905	12,618,665	12,615,367	12,612,416	12,608,838	12,605,638	12,602,265
Total_seed_capacity(Ageclass1,Substock5)	16	2,546,624	2,541,348	2,541,215	2,540,363	2,539,710	2,539,047	2,538,453	2,537,732	2,537,088	2,536,410
Total_seed_capacity(Ageclass1,Substock6)	11	2,326,511	2,321,691	2,321,569	2,320,791	2,320,195	2,319,589	2,319,046	2,318,388	2,317,800	2,317,179
Total_seed_capacity(Ageclass1,Substock7)	81	2,115,453	2,111,071	2,110,960	2,110,252	2,109,710	2,109,159	2,108,665	2,108,067	2,107,532	2,106,968
Total_seed_capacity(Ageclass1,Substock8)	34	39,123,688	39,042,645	39,040,591	39,027,501	39,017,482	39,007,285	38,998,159	38,987,095	38,977,202	38,966,771
Total_seed_capacity(Ageclass1,Substock9)	01	961,253	959,262	959,211	958,890	958,643	958,393	958,169	957,897	957,654	957,397
Total_seed_capacity(Ageclass1,Substock10	42	3,683,410	3,675,780	3,675,586	3,674,354	3,673,410	3,672,450	3,671,591	3,670,550	3,669,618	3,668,636

RESTOCKING AREA REQUIREMENT (m2)

Time	Total_required_restocking_area
0	150
1	89
2	72
3	75
4	58
5	24
6	55
7	47
8	51
9	50
10	50
11	48
12	50
13	49
14	50
15	50

Figure 3.20: Output window 6.

Finally, outputs windows 7 and 8 (Fig. 3.21 and 3.22) show in that order, a detailed tabular specification of the 'investments', 'costs', 'incomes', 'payment', and 'net present value' of the project, all separately estimated for the wild, the released and as sum of both components, and a time-series 'cash flow' curve of the project.

ECONOMIC EVALUATION OF THE PROJECT

WILD AND RELEASED STOCK POPULATION SPECIFIC INVESTMENT ($/year)

Time	0	1	2	3	4	5	6	7	8	9	10	
Initial_investment(Wildstock)	0	0	0	0	0	0	0	0	0	0	0	
Initial_investment(Releasedstock)	0	0	0	0	0	0	0	0	0	0	0	
Total_initial_investment	0	0	0	0	0	0	0	0	0	0	0	

WILD AND RELEASED STOCK POPULATION SPECIFIC COSTS ($/year)

Time	0	1	2	3	4	5	6	7	8	9	10	
Fleet_maintenance_costs(Wildstock)	1,072,636	845,545	797,277	786,985	784,013	813,554	876,095	878,458	887,961	889,088	889,532	887
Property_costs(Wildstock)	649,890	512,300	483,055	476,819	475,019	492,917	530,809	532,241	537,999	538,682	538,951	537
Monitoring_costs(Wildstock)	2,582,273	2,035,572	1,919,370	1,894,594	1,887,439	1,958,556	2,109,117	2,114,806	2,137,684	2,140,397	2,141,467	2,136
Fishing_costs(Wildstock)	2,886,818	1,766,220	1,609,880	1,282,191	566,674	965,576	1,133,428	1,203,686	1,232,917	1,245,092	1,250,142	1,252
Fleet_maintenance_costs(Releasedstock)	0	227,091	275,359	285,651	288,623	259,083	196,542	194,179	184,675	183,548	183,104	185
Property_costs(Releasedstock)	0	137,590	166,835	173,071	174,871	156,973	119,081	117,649	111,891	111,208	110,939	112
Monitoring_costs(Releasedstock)	0	546,701	662,902	687,679	694,834	623,717	473,156	467,467	444,589	441,875	440,806	445
Fishing_costs(Releasedstock)	0	0	0	0	0	195,803	177,683	149,864	144,172	121,324	69,292	94
Restocking_costs	2,951,459	1,882,831	1,582,308	1,621,793	1,335,621	726,962	1,279,702	1,137,463	1,206,323	1,192,707	1,186,622	1,151
Operational_costs(Wildstock)	7,191,618	5,159,637	4,809,582	4,440,589	3,713,144	4,230,603	4,649,449	4,729,191	4,796,560	4,813,259	4,820,092	4,814
Operational_costs(Releasedstock)	2,951,459	2,794,213	2,687,405	2,768,194	2,493,950	1,962,539	2,246,164	2,066,623	2,091,651	2,050,663	1,990,763	1,989
Total_operational_costs	10,143,077	7,953,850	7,496,987	7,208,783	6,207,094	6,193,141	6,895,613	6,795,813	6,888,211	6,863,922	6,810,855	6,803

WILD AND RELEASED STOCK POPULATION SPECIFIC INCOMES ($/year)

Time	0	1	2	3	4	5	6	7	8	9	10	
Incomes(Wildstock)	29,893,186	18,669,977	17,744,263	13,960,656	5,687,771	11,054,608	12,725,591	13,425,016	13,716,004	13,837,211	13,887,488	13,907
Incomes(Releasedstock)	0	0	0	0	0	2,339,089	2,001,579	1,680,451	1,629,643	1,360,229	752,770	1,087
Total_incomes	29,893,186	18,669,977	17,744,263	13,960,656	5,687,771	13,393,697	14,727,170	15,105,467	15,345,647	15,197,440	14,640,258	14,995

WILD AND RELEASED STOCK POPULATION SPECIFIC PAYMENT ($/year) AND NET PRESENT VALUE ($)

Time	0	1	2	3	4	5	6	7	8	9	10	
Payment(Wildstock)	22,701,568	13,510,340	12,934,681	9,520,067	1,974,627	6,824,005	8,076,142	8,695,825	8,919,444	9,023,952	9,067,396	9,093
Payment(Releasedstock)	-2,951,459	-2,794,213	-2,687,405	-2,768,194	-2,493,950	376,550	-244,585	-386,171	-462,007	-690,434	-1,237,993	-901
Total_payment	19,750,109	10,716,127	10,247,276	6,751,873	-519,323	7,200,556	7,831,557	8,309,654	8,457,437	8,333,518	7,829,403	8,192
Net_present_value(Wildstock)	22,701,568	34,764,372	45,075,820	51,852,016	53,106,927	56,979,051	61,070,676	65,004,226	68,606,639	71,860,767	74,780,226	77,394
Net_present_value(Releasedstock)	-2,951,459	-5,446,292	-7,588,675	-9,559,021	-11,143,971	-10,930,306	-11,054,221	-11,228,905	-11,415,502	-11,664,479	-12,063,080	-12,322
Total_net_present_value	19,750,109	29,318,079	37,487,145	42,292,995	41,962,956	46,048,745	50,016,455	53,775,321	57,191,138	60,196,288	62,717,146	65,072

Figure 3.21: Output window 7.

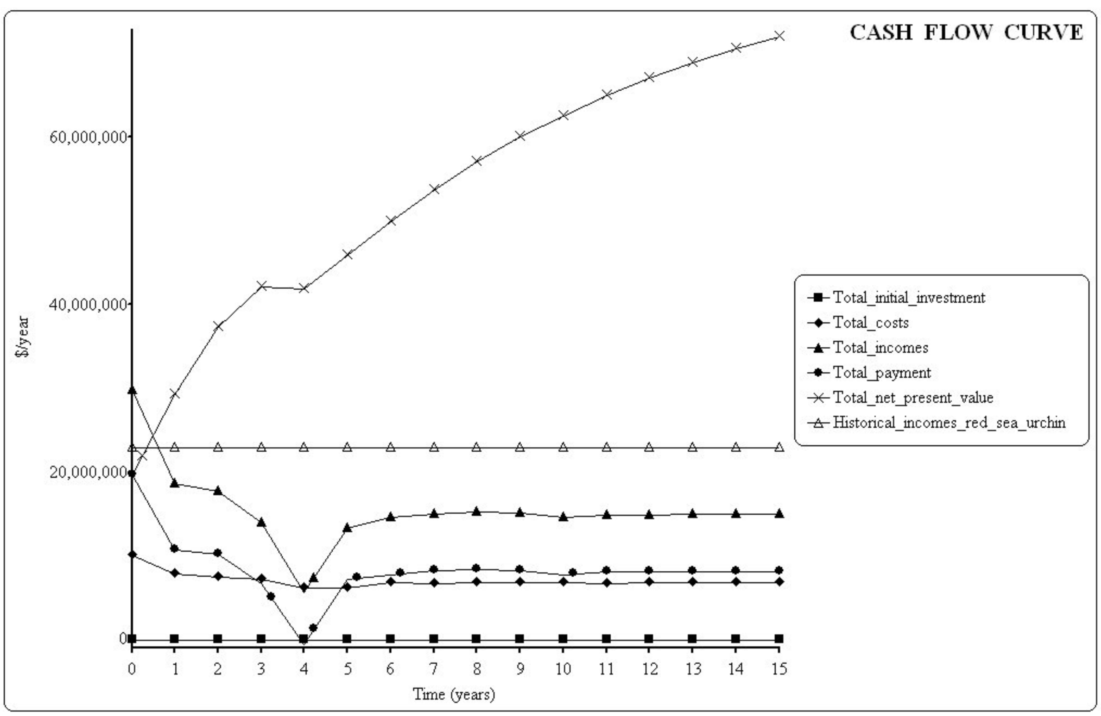


Figure 3.22: Output window 8

3.4.8 MODEL OPERATION

The simulation model is run Powersim Constructor® 2.51, and once installed can be opened directly by double-clicking from Windows Explorer at its directory location or alternatively browsing the file from Constructor under 'Open' at the 'File' main command bar.

Once the model is open, the user must control the 'RUN- STEP' command and input all required data into the 5 input windows of the software. Input can be made either by scrolling the control bar on each variable or by right- clicking on the correspondent value box to edit more precisely the number for the variable.

After all input variables have been correctly filled out; the model can either be run on a time step basis by using the 'RUN- STEP' command or on a continuous basis by deactivating the 'PAUSE' until the end- time is reached.

The model can be stopped at any time using the 'STOP' command. Input variables can then be modified and outputs can be printed at any time. The model then can be re- run from the beginning or continued from the time at which was stopped.

The software takes about 3 seconds to complete the full evaluation time at one run (15 years on a one year time-step), when is operated on a typical laptop or desktop computer with a 400Mhz processor. It does not therefore require a very fast or sophisticated computer system.

Model settings and results can be saved under any name by using the 'save as' under 'File' command. The user cannot edit the software in any way.

3.5 DISCUSSION

The present study was focused on the development of a simulation model, which allows the exploration of biological effects, spatial dynamics and economic projections resulting from alternative coastal management plans for a red sea urchin fishery, operating under the system of AMEBR in Chile.

This was achieved using dynamic systems modelling methodology and a model-maker platform to support structural construction, equation deduction, and computer implementation of the conceptual model developed.

Four linked submodels, the biological, the production, the socio-economic and the spatial submodel, with 126 variables and 2,873 array/vector elements, are integrated into the final output model structure. The final version of the bio-socio-economic simulation model consisted of five input windows and eight output windows, working in a Windows®-based platform and running on Powersim Constructor 2.51®. These describe the stocks component dynamics, the projection of commercial and production targets of the system, the socio-economic requirements and financial evaluation of the project, and the spatial dynamics of potential restocking sites in the management area.

Final selection and inclusion of determinant factors was acknowledged as a highly difficult undertaking when modelling the system. Even though several influencing factors were individually identified, their formal introduction into the model structure was not possible in many cases. This was mainly determined by the lack of knowledge of relevant causal relationships among factors, but more importantly caused by a total unavailability of factor-related data. This restricted the inclusion of a number of relevant parameters into the final model, and forced the need to adopt a flexible approach towards making, as much as possible, a realistic and precise, but also clear, understandable and applicable model for a wide-range of users.

As noted by Muir (1996), no model in ecologic/economic systems can achieve all major quality attributes; i.e.: realism, precision and generality. This study is a good example, whereas attempting to be most realistic and precise, the model was very specific to both the species (red sea urchin) and the system's functioning framework (AMEBR). To the same extent, realism was also restricted by the lack of knowledge in causal relationships and data availability, but precision was fairly good on the computerized model implementation on the working platform.

At this point, the model-maker platform (Powersim Constructor®) was assessed as a highly satisfactory, flexible, cost-effective visual tool, but mostly user-friendly and descriptive software for modelling aquaculture/fishery-based systems. Recently, this software was successfully used on similar applications, specifically for development of the bio-economic simulation model LOBST.ECO, whose main objective was to evaluate biological effects and economic outputs resulting from various fishery management regulations within the framework of mass releases of the European lobster juveniles in Norway (Borthen *et al.*, 1999). The authors played an important role during early stages of this work, as a source of information and support to find the software platform ultimately used for modelling the system.

The BSESM was originally designed to model the red sea urchin *Loxechinus albus* fishery along the coast of Chile. It therefore had implicit assumptions about the life cycle of the organism, which should be considered before using it for other sea urchin or benthic species. However, allowing for species-related structural modifications, the present model could easily be modified to be more generic. Thus, if species-specific parameter data are available, this simulation model could be applied to virtually any commercial benthic invertebrate fishery under management within the system of AMEBR or similar fishery regime.

The BSESM can be used to design and evaluate alternative management plans and multiple macro-scenarios. Hence, the model allows for flexible planning, which may or not include restocking exercises, and changeable variable levels of exploitation for managing the fishery. Therefore, the user (fishery scientist/manager, fishermen association or resource user, government fishery agency) can use this tool to analyse the state and dynamics of the fishery when subjected to diverse management regimes. Socio-economic projections generated and population dynamics can then be used to support decision-making for both short and long-term administration of the fishery, without any intervention on the real system.

Although the model is mostly deterministic, when run from its base platform on the simplest way (Powersim Constructor 2.51®), it can also be set up to include and analyse the effects of stochastic variability in one or more input parameters, if run using an alternative software (Solver 2.0®), which by using a rather more sophisticated running-methodology, can be used to automatically search for optimal decisions and investigate relationships and risks in the model (Anonymous, 1999). Having built an online model, Powersim Constructor can be initially used for running and testing the model using multiple macro-scenarios (manual input-output model execution). Secondly, Solver can be utilized for optimising the model to search for decisions that produce the best results (optimisation routines), investigate what effects uncertainties may have on the results (sensitivity analysis), and finally find a set of decisions to achieve a given objective while keeping the risk below a given threshold (risk management and strategic planning).

The running methodology can therefore be structured on an initial rather deterministic study, and a final in depth examination, including stochastic variability analysis and risk management of uncertainty in the system. These procedures were fully covered, on the basis of a real data case study in the final stage of this work (Chapter 5).

The population model, in the biological submodel, was developed to allow separate analysis of each stock and its dynamics in response to management measures and exploitation patterns. The final model consisted of two age-structured stock components (wild and released), considering 12 ageclasses and up to 10 substocks in each, sharing a given coastal area. Wild and released components are age-structured stocks with negative exponential mortality, including the constant instantaneous rates of natural and fishing mortality**.** Natural mortality is differential to wild and released individuals, and uniform to all ageclasses starting from the first and cero to the last. Fishing mortality is also constant for all individuals in the commercial stock, and cero for individuals under the minimum legal commercial size, being uniform to wild and released individuals. Natural recruitment is independent of the local parental stock and set to be a user-defined input value in the system, generated from external sources or coastal areas. Wild and released stock components share the conditions of study, parameter values and assumptions defined for modelling the system.

Major critical assumptions on the biological submodel referred to the age independent uniform natural mortality, and natural recruitment independent of the size of local parental stock.

Here, the first was probably the most unrealistic assumption in the model; as for most marine resources natural mortality is undoubtedly age/size dependant, being influenced by a number of factors, such as ecologic interactions (competence and predation) and environmental conditions (habitat conditions and food resource availability).

Even though natural mortality rates are well known for other red sea urchin species (Morgan, 1997), this is not the case for *L. albus*. Relevant research on this subject is scarce, and most studies have evaluated natural mortality of restocked sea urchins for relatively short periods of time under dissimilar conditions and at different geographic locations along the coast of Chile (Bustos *et al.*, 1991; Stotz *et al.*, 1992; Olave *et al.*, 1993; Figueroa, 2000). Final results reported have been based on accumulated mortality across the full period of study, rather than stage-based mortality rates. This imposed serious restrictions for the inclusion of this parameter on a more realistic stage-basis in the population model. Similar simplifications, using an annual instantaneous natural mortality fixed for all size/age-classes integrating a given subpopulation, have been used on population models for the red sea urchin fishery in California (Bostford *et al.*, 1999). In addition, in view of the large number of variables constituting the BSESM (2,873), the inclusion of an age-based mortality rate was also constrained by the maximum number of variables (array elements) allowed in a model designed on Powersim 2.51 (3,000 variable elements).

Although a stock-independent natural recruitment unaffected by fishing pressure is a most unlikely and unreal assumption within the traditional population model (Seijo *et al.*, 1997), the situation is rather inconsistent for echinoderms, specifically for sea urchins. In fact, there is no evidence that local stock size of echinoderms influences recruitment, other than the trivial case where a stock of zero size produced zero recruits (Ebert, 1983). Recruitment in sea urchins shows both high temporal and spatial variation, as a result of long development times and consequent large distances that planktonic marine larvae may travel until they settle (Morgan *et al.*, 2000). The task of understanding the complex relationships between physical transport and recruitment has been focus of a number of studies on sea urchins (Ebert and Russell, 1988; Wing *et al.*, 1995; Miller and Emlet, 1997). However, there is still little understanding of this variability in recruitment over the ranges of entire metapopulations linked by larval dispersal (Bostford *et al.*, 1994).

Density-dependence in the recruitment process has been a critical question in population models for sea urchins (Bostford *et al.*, 1999). Density-dependence in fecundity occurs in sea urchins, but typically only at very low densities (Levitan, 1989). Density-dependence in the larval stage is not known, and not suspected to occur (Bostford *et al.*, 1999). Hence, relation of local stock to recruitment would be determined by some known density-dependent mechanisms, such as the protection of juveniles under the spine canopy of adults (Tenger and Dayton, 1977), and the decreasing efficiency of broadcast spawning (Levitan *et al.*, 1992). However, survival across the larval stage, and the origin of recruits to each site are not known (Bostford *et al.*, 1999). In recent studies, Morgan *et al.* (2000), found that recruitment patterns in northern California's red sea urchin population would be determined by the effect of coastal circulation on larval delivery during relaxation of upwelling, and not a result of the positive effect of the spine canopy on juvenile survival.

With regard to the Chilean red sea urchin, much less data is available and consequently there is little understanding about recruitment processes. Relevant studies, though, have indicated that the situation would be similar to the one previously described, in the sense that *L. albus* shows a highly variable recruitment pattern (Bustos *et al.*, 1990; 1991). Evaluating natural recruitment effects of a restocked population in southern Chile (Chiloe), Bustos *et al.* (1991) found that recruitment would be directly associated with the presence of adults. As in the inner sea of Chiloe, water circulation would be only determined by tidal currents (Bustos *et al.*, 1990), this study concluded that major source of recruits would be hypothetically represented by deep subtidal adult populations, but also by the contribution of larval dispersion from other locations. Similar results were reported previously by Moreno and Vega (1988), describing recruitment for a natural population at the marine reserve of Mehuin (Chiloe). In other sites, e.g. north and central coast of Chile, events in offshore waters, such as wind-driven up welling and local swells are different, and therefore change the composition of the intertidal community. For this, the supply of larvae and effective recruitment may be determined by other factors, such as the regional pattern of circulation.

Even though this population model did not implicitly include any density-dependent mechanism, the effect of both the adult spine canopy as protection from predation for juveniles (Tenger and Dayton, 1977), and the Allee effect associated with the forecast spawning (Levitan *et al.*, 1992; Lunquist and Bostford, unpublished manuscript) could be incorporated indirectly in the analysis. As proposed and applied by Bostford *et al.* (1999), both effects would present approximately a linear mechanism between adult density and recruitment, and were included into their population model only as a great uncertainty in recruitment. In addition to this, as circulation patterns and source of recruits are not known, an even greater uncertainty in recruitment was considered in order to deal with this factor in the final stage of this study. This approach was also suggested when analysing the model structure and operation with relevant experts (Emlet pers. comm.).

Since this model is based on a benthic species, key assumptions underlying the biological submodel should be also analysed in contrast to the relative limited applicability of the classic population model for finfish species to sedentary resources (Seijo *et al.*, 1997). In fact, foremost assumptions of the logistic surplus yield and dynamic aggregation models are not always valid in sedentary resources, because:

- their spatial distribution is usually aggregated (Elliot, 1977; Hall, 1983);

- their low or null mobility restricts its redistribution in the fishing area (Caddy, 1989a; b);
- the fishing strategy tends to sequentially exterminate patches until they turn unprofitable (Hancock, 1973; 1979; Caddy, 1975; 1979a; b; Conan, 1984; Oresanz *et al.*, 1991); and
- individual growth and mortality parameters depended on environmental and population size conditions varying on time and space (Oresanz, 1986; Holm, 1990; Raimondi, 1990; Possingham and Roughgarden, 1990; Defeo, 1993).

Within this study, the spatially heterogeneous and aggregated distribution of the resource was taken into account subdividing each stock component into up to ten substocks, on the basis of their evident isolated localisation in different zones of the study area. Based on a system delimited by a relatively small coastal area, a standard environmental condition was also assumed for all these substocks or patches, therefore resulting in the same growth, and natural mortality, and being subject to equal fishing pressure. Hence, even though each stock component could be divided into up to ten discrete substocks, the model did not considered separated subpopulations with differential parameters (excepting for the natural mortality rates for wild and released individuals) and environmental conditions.

The previous approach though, has been suggested as a way to relax the underlying assumptions for resource spatial homogeneity and fishing effort in sedentary species (Caddy, 1975; Slcuzanowsky, 1986; 1994). However, the approach of using several discrete subpopulations (even when linked by larval dispersal patterns) should be only considered if dealing with stocks with an extensive geographic distribution, and then subjected to high variability and different environments (Seijo *et al.*, 1994b;c). This methodology was used by Lockwood (1998) when modelling the population of the red sea urchin *Strongylocentrotus franciscanus* fishery for examination of the effect of spatial management, in addition to conventional management by size limit and fishing effort. This study was based on the evaluation of 24 subpopulations geographically distributed in different locations along the entire northern coast of California.

Bearing in mind that in very few specific cases the management area may be sufficiently large to cover a lengthy shoreline, or when studying more than one management area simultaneously, the modification of the population model to discrete subpopulations will be required, but only if there is evidence of variable environmental conditions to assume separated subpopulations. However, this situation is not likely to happen, as management areas must be very delimited and most do not cover such large coastal extensions.

In contrast it would be rather more reasonable to consider in future models, a substock-specific treatment for fishing effort, and therefore to provide the option of differential fishing pressure within the major substocks inhabiting the coastal lease. This would certainly reflect a more realistic model of the exploitation pattern for small-scale fishing of most commercial benthic resources in Chile. Thus, the model could be improved by introducing a set of optional strategies for spatial allocation of the fishing effort, among which could be included:

- proportional allocation to resource spatial distribution (Caddy, 1975),
- sequential allocation of fishing effort on most abundant patches (Hilborn and Walters, 1987);
- spatial allocation of fishing effort proportional to the variable costs and the distance friction factor, i.e. the non-monetary cost associated to the distance, and the possibility of finding optimum levels of the resource (Defeo *et al.*, 1991; 1994c; Cabrera, 1995; Hernandez, 1995).

Together with the earlier approach of applying a classic population model to sedentary species, it has also been suggested to use stochastic models to make implicit the random error in conjunction with the use of probability distributions for prediction of critical causal relationships in the model (Bostford, 1986; Seijo, 1987; 1989; Fogarty, 1989; Seijo and Defeo, 1994b; Seijo *et al.*, 1994b). This may help to build more comprehensive models, integrating the inherent characteristics of the resource, and taking into account the uncertainty associated with most biological, environmental, social and economic variables (Lewis, 1982; Andersson, 1984; Sissewine, 1984a; b; Seijo, 1986; Hilborn and Walters, 1987). This study considered detailed examination and analysis of variability within the factors in the model, in order to identify major critical assumptions and evaluate their effects on the simulated results through sensitivity analysis. Major biological factors analysed on that stage, were: the differential constant natural mortality rates and total natural recruitment in the system.

The spatial distribution of stocks and fishing effort in aggregating species such as benthic resources like sea urchins could result in CPUE being a poor index of overall abundance (King, 1995). In highly mobile species (e.g. finfish) or pelagic species, where stocks are well mixed by migration, spatial effects are likely to be of less concern than in sedentary species, and therefore CPUE can be related directly to stock abundance. In this context, in the socio-economic submodel it was assumed the catch rate to be fixed and independent of the stock abundance. Thus, harvesting costs were estimated as a function of the amount harvested in the fishery. Certainly, this is not the usual situation for most fisheries, where costs tend to be proportional to fishing mortality or the catch rate is related to stock abundance. In the cases of benthic species, the catch rate for a particular fishing trip will vary largely depending on the skill and the luck of the fisher (King, 1995). However, in this particular framework (AMEBR), based on a relatively small coastal area, where fishermen know accurately the exact location and have an estimate of the abundance of major stocks, there is no major searching process (time/costs) rather than selecting and travelling to target stocks and harvesting them. This is even more important if consider that natural stocks are very well delimited, and being a benthic sedentary species movement is also extremely restricted. As a result, the catch cost-efficiency during fishing operations improves significantly, being increasingly better-planned, mechanized, more certain and less dependent on the luck, skill or searching process.

Being an important intermediate linking element between the cove's socio-economic requirements and the production management of the resource, the aim of the production submodel was to facilitate quantitative estimation of production targets of the system in the form of a total population. For this reason this submodel constituted the core for dimensioning and planning the restocking element as a management tool, integrating the fundamentals underlying on the production system proposed.

Explicitly, this submodel works on the basis of a dynamic system that could broadly show two different level states:

- a balanced or positive level of recruitment; and
- an unbalanced or negative level of recruitment.

The balanced state represents a system that sustains a population that presents sufficiently robust recruitment levels to support historical levels of exploitation of the resource. Under these circumstances, the system should not require an external input, i.e. restocking element, in order to achieve sustainable production. In contrast, the second possible state is determined by a system, in which population conditions and recruitment are below a given threshold ('recruitment target') to support commercial exploitation of the resource. Here, if restocking is considered for managing this unbalanced system, the submodel calculates the number of individuals required to balance the population, on the basis of the recruitment level required. Additionally, within these general states, the system may present many equilibria, ranging from an unexploited to a heavily overexploited population.

The model assumes, therefore, that the restocking element constitutes an external contribution to stock the fishery, at which natural recruitment is limited, uncertain and highly variable, and that under historical levels of exploitation has achieved a state of overexploitation. As a result, the magnitude and frequency of this contribution is not fixed, and may vary dynamically according to the predicted state of the stocks.

Regardless of the management option for inclusion or exclusion of restocking and the levels and plans of exploitation, the key element to be defined will be the population level or production target for management. This constituted the point of reference for estimating the target commercial stock of the system, which was then processed through the socio-economic submodel. In this submodel, this essential element was estimated on the basis of the expected incomes of local fishermen and the mean landed price of the product. Expected incomes were defined as a function of the historical incomes or captures traditionally generated from commercial fishing of the red sea urchin in the management area.

Though this approach was used to define the production target for the system, alternative methodologies may be also used for this purpose, e.g.: estimated carrying capacity for the calculation of the optimum population level. This choice will involve establishing clear objectives for management of the fishery. Hence, if management is purely for conservation, population targets may have to prioritise ecological and environmental aims. However, if management is focused on restoration of a commercial fishery, the establishment of production targets may be preset by the social and economic requirements, while clearly avoiding trespassing the environmental limits of the system. This will remain a major issue for further analysis and discussion.

Having defined the production target or population level desired, the management plan for a commercial fishery will rely on and result in a number of social and economic inputs and outputs. For this, a complete financial evaluation tool was constructed within the socio-economic submodel, to allow the user to set up the economic needs of the community and analyse the financial dynamics and repercussions of the project resulting from the management and exploitation strategy applied to the fishery.

As previously described, relatively few stocking programmes have been designed considering economics issues, especially for the marine environment (Baily, 1991b; Welcomme, 1998; Langton and Wilson, 1998). Noted by Borthen *et al.* (1999), any final assessment of a stock enhancement project should involve issues as to whether the releases enhance the stock and also not cause a displacement of wild animals, as well as economic evaluations such as profitability and viability. Considerable economic research is needed to determine and improve cost-effectiveness of marine restocking projects (Bannister, 1991), though as enhancement is being increasingly considered worldwide, more reports on economic models of ongoing and proposed programmes are becoming available (e.g.: Arnason, 1991; Sandberg, 1991; Kitada *et al.*, 1992; Peterson *et al.*, 1995; Moksness, 1997; Moskness and Stole, 1997; Wilson *et al.*, 1997; Borthen *et al.*, 1999, del Campo and Perez, 1999; Vega, 1999).

There is also a great need for economic evaluation of benthic management programmes in Chile. Although, the AMEBR may offer one of the best approaches to achieve sustainable fishing of inshore benthic zones in Central Chile (Castilla and Fernandez, 1999), this is totally subject to the adequate consideration of the various factors related to the use and/or preservation of resources. Gonzalez (1996) classified these factors into four major groups-biological and ecological, technological, economic, and social. Biological and ecological, factors are the assimilative and carrying capacities of the given environment, the resource abundance and reproductive and growing rates of the species. Technological factors include the knowledge, technology and tools used in the productive processes. Economic factors involve capital, labour, market conditions, and individual preferences. Finally, the social structure defining individual preferences, the cultural context and the legal institutional framework restricting the exploitation or conservation of the resources constitute the main social factors.

Providing a wider and sectored analysis, Gonzalez (1996) recognized that irrational exploitation implies alterations to the environment, as well as to the economic activities based upon it. Likewise, both factors and related issues and constraints must be considered in the establishment of the AMEBR through an ecosystemic, dynamic, and quantitative approach. From a similar point of view, Stotz and Gonzalez (1997), suggested that management decisions for promoting the sustainable use of fishing resources in Chile, should be based on investigations of the biological and environmental, as well as the economic and social aspects. In this context, they recognized interrelations among these factors, consideration of which may determine the success or failure of management plans.

In consequence, governmental fisheries-related institutions have fairly recently acknowledged the need for considering economic and social issues for the management of benthic resources under the AMEBR scheme. Hence the regulations for the BLS have made explicit the requirement for a socio-economic characterization, and the inclusion of indicators for monitoring and evaluating social and economic performance resulting from the proposed management and exploitation plan of the target resource at a given coastal area (Subsecretaria de Pesca, 2001). This must include a pre-evaluation of the MEP proposed and an additional methodology to record, monitor and assess the management programme in socio-economic terms. For this, some specific economic indicators have been suggested for fishermen's associations to consider, among others (Subsecretaria de Pesca, 2001):

- registration of landed price trends;
- analysis of cost-benefit ratio;
- determination of marginal profit for individual fishermen;
- assessment of the relative commercial importance of the target resource;
- identification of commercialisation sites and process description;
- calculation of various indices of economic productivity; and
- estimation of income distribution among members of the association.

Within this setting, the present socio-economic submodel may provide a user-friendly device, especially designed for the system, which allows for case study-based project analysis, but also as provides means for a wider examination of the system of administration. This submodel integrated the main resource-specific economic and social elements interacting in a small-scale cove in Chile. Required input parameters can be well fulfilled with existing and known real-data, available to most fishermen's associations. As a result, this submodel covered, most if not all of the socio-economic aspects required to be assessed by fishery managers or technical units representing fishermen's associations before the Undersecretary of Fisheries. Hence, this component could be used to support resource management and planning from the very first stages when requesting the management area, to subsequent stages of monitoring and assessing the resulting socio-economic performance.

Though not explicitly, the BSESM included environmental factors influencing stock enhancement within the spatial submodel. For this, restocking was analysed in terms of the spatial component of the environment, specifically focused on estimation of the total area required to perform a given restocking exercise, the inclusion of potential restocking site area availability and suitability, their coverage process as restocking take place, and the estimation of a spatial index of carrying capacity of the system as a function of the total seed capacity of each restocking site.

This submodel certainly constituted a fundamental element in the model developed. Being in essence a sedentary species, the red sea urchin strongly relies on the spatial component of the environment for it vital functions and development. Appropriate assessment of spatial components of the environment constitutes an essential element in management for this species and any other sedentary species, and therefore must be included in the bio-socio-economic analysis (Seijo *et al.*, 1997). This should provide a more complete specification of the resource, not considered yet on traditional population theory (Woolin, 1974; Yodniz, 1978; Quinn, 1979; Hastings, 1980; Sebens, 1982).

For this reason, recognizing the importance of space-related issues for management, a separate but closely linked GIS-based model was developed, for spatial analysis of major factors influencing restocking activities for this species and to support decision-making for site selection. Further details of the geographical information systems model for restocking of sea urchins (GISRM) are presented on the next chapter.

The need for further inclusion and analysis of environmental/ecological factors within the model was also clearly acknowledged. Among these it would be suitable to include implicitly a direct estimation of the carrying capacity of the system, and relevant indices to assess environmental sustainability of the ecosystem, and the influence of predation on the population as management takes place.

The model created may be used to analyse stock dynamics, spatial processes and carry out financial pre-evaluation, monitoring, and post-evaluation, purely focused on alternative management for the red sea urchin at a given AMEBR. It may also be used for detailed examination of specific critical aspects in a wider perspective of the system of AMEBR, as for example: mass releases of hatchery-reared juveniles as major tool to support overexploited wild stocks or the believed high-cost property tax imposed to fishermen association for the AMEBR, or the interrelations between the size, costs and incomes of the management area. Some of these issues were covered on the last stage of this work, where the bio-socio-economic simulation model was run using real case-study data to analyse both, specific management plans for the red sea urchin, and the system of management and exploitation of benthic resources in a wider perspective.

In specific terms, this model can be very useful to support decision-making in management of sea urchins, in particular when including stock enhancement as a major element. The actual regulations for AMEBR permit restocking of hatchery-reared individuals only as a way to support recovery and enrichment of natural stock, and so every release must be very well estimated, programmed, but mostly thoroughly justified. Among a number of technical and operational aspects (e.g.: origin of the juveniles, transportation methods, restocking material and labour, identification and characterisation of restocking sites, etc) to be described in the final methodology, the proposed restocking programme must make clear the number of individuals to be released, their size-at-release and population size structure, and the mean restocking density (Subsecretaria de Pesca, 2001). In addition to this, a comprehensive methodology must be described for monitoring the released population, which must cover population density, size-structure, growth and mortality rates. All this information has to be properly reported and analysed.

Though all these requirements have been imposed for implementation of a restocking programme, there is as yet no standard methodology for dimensioning and programming mass releases. Hence, despite enormous technical progress in hatchery production of sea urchins in Chile, restocking of juveniles has not yet been widely implemented, mostly as result of inconsistent or unavailable techniques to estimate, support, but for the most part to justify restocking before the Under Secretary of Fisheries. As a result, very few AMEBR have attempted to include management of sea urchins on the basis of stock enhancement.

Within this context, the present model may contribute to the system as a tool to analyse and effectively support restocking and other management strategies for the red sea urchin, providing the fishermen's associations and their technical units with a standard methodology to, formulate, evaluate and analyse management plans. This and other aspects associated with the practical application and implementation of the BSESM, within a local scale of fishermen associations, and in the wider scale of the fishery system of AMEBR in Chile, are further analysed on the last stage of this research.

CHAPTER 4

THE GEOGRAPHICAL INFORMATION SYSTEMS-BASED RESTOCKING MODEL (GISRM)

4.1 INTRODUCTION

4.1.1 SITE SELECTION FOR RESTOCKING AQUACULTURE

Substantial attention and effort has been focused on the development of suitable techniques for effective husbandry and commercialisation of a variety of aquatic animals and plants, including various algae, invertebrates such as clams, sea urchins, gastropod molluscs and shrimps, and many finfish species (Arnold *et al.*, 2000). By contrast, significantly less effort has been expended to assist in the crucial process of identifying and selecting a site for field grow-out of cultured species (e.g.: Kapetsky *et al.*, 1987; Meaden and Kapetsky, 1991; Ross *et al.*, 1993; Friddley, 1995; Kapetsky and Nath, 1997; Aguilar-Manjarrez and Nath, 1998; Parker *et al.*, 1998; Rubec *et al.*, 1998; Perez-Martinez, 2002, Perez-Sanchez, 2002).

Restocking aquaculture is the enhancement of freshwater or marine finfish, molluscs, crustaceans and other organisms, with the main objective of stock recovery and/or improvement, compensation for depletion and/or protection schemes (Cowx, 1998). Hence, a restocking exercise is based on the release into their natural habitat of juvenile or seed stages, which have been either collected or hatchery-reared. As a result, field grow-out is essential for implementation and to obtain the expected production, recovery of natural banks and/or desired economic returns from the fishery. Successful large-scale releases therefore require the correct selection of a restocking site, showing specific biotic and abiotic characteristics that favour the overall survival, growth and development of juveniles (Bustos *et al.*, 1991). Many authors have emphasized the importance of careful site selection before starting enhancement programs (Tegner and Butler, 1989; Schiel, 1993; Seki and Tanigushi, 2000; Shepherd *et al.*, 2000). It is important to take the natural history of the animal into account as well as the history of the site. (Huchette *et al.*, 2000).

Restocking programmes have been primarily targeted on migratory (e.g. Salmonids), stationary, (e.g. Molluscs) and marine species, where recruitment of juveniles is limiting production of harvestable stocks, for example: Cods and flatfishes (Isaksson, 1988). In the case of marine sedentary species that inhabit the sea floor, or live attached to artificial structures, such as bivalve molluscs, gastropods and echinoderms, the inherent characteristics of their biology and population dynamics are different to those observed for pelagic fisheries. Consequently, this imposes important restrictions with regard to the application of traditional resource management and exploitation plans (Seijo *et al.*, 1997). For this reason, bioeconomic models for these species must consider the spatial components of the distribution, exploitation, ecological interactions and the effect of environmental gradients into size/age distribution of stocks.

This spatial component is determined principally by the species essential habitat, which is the place that an animal uses for spawning, feeding, nursery, migration and residence functions; most habitats perform only a subset of these functions (Edwards *et al.*, 1992). The habitat of a fish or shellfish may change during its life history, or because of seasonal and geographic distribution, abundance, and species interactions. If habitat functions are constrained, then the needs of the species cannot be achieved, and the potential of the habitat to support living resources are limited (Edwards *et al.*, 1992).

Space is a distinctive element of the dynamics of sessile marine invertebrates, and the obvious limiting resource. For this, is useful to have a theory that explicitly treats the acquisition and release of space (Roughgarden *et al.*, 1985). This would provide a more complete specification of the resource, which has not yet been considered in traditional population theory (Woolin, 1974; Yodniz, 1978; Quinn, 1979; Hastings, 1980; Sebens, 1982).

As it is essentially a sedentary species, the red sea urchin has a highly aggregated spatial distribution and a relative low mobility, forming patches where growth and mortality parameters rely on local environmental conditions. As coastal environmental conditions are also variable in time and space, vital development of this species is closely linked to the spatial components of the environment in its natural habitat.

Appropriate assessment of spatial components of the environment for the selection of suitable sites for a restocking exercise certainly constitutes an essential element in management of this species. Together with the seed size, quantity and stocking density, seeding technique and management measures, efficient site selection is perhaps the most relevant technical factors influencing long-term effectiveness of a restocking programme for benthic resources.

Site selection for integrated restocking and management programmes is even more relevant in the context of the Chilean system of Management and Exploitation Areas of Benthic Resources. This scheme involves the lease of coastal areas to artisanal fishing associations for management and exploitation of benthic resources of commercial interest. Hence, considering a limited coastal area for management of various benthic resources of specific habitat requirements inevitably requires strategic administration and spatial optimisation. More importantly, taking into account the annual management tax per managed hectare, the more area-efficient is the lease, the more cost-effective will be the management plan in the long-term for the benthic resources concerned.

In summary, considering the management, biological and economic implications, appropriate site selection for either large or small-scale application to coastal leases for management, restocking and exploitation of benthic resources is essential for achievement of long-term success of the production system.

4.1.2 GIS FOR NATURAL RESOURCES MANAGEMENT AND SITE SELECTION

In technical terms, a Geographical Information Systems (GIS) is an “integrated assembly of computer hardware, software, geographic data and personnel designed to acquire, store and manipulate, retrieve, analyse, display and report all forms of geographically referenced information geared towards a particular set of purposes” (Borrough 1986; Kapetsky and Travaglia, 1995). Perez-Martinez (2002) defined GIS more simply as a *tool* for management of information of any kind according to where it is located.

Planning and management of natural resource based activities requires the interpretation, assessment and cross-referencing of the wide range of contributory factors. Within this framework, GIS provides a tool under which a protocol for the structured analysis of spatial data for natural resources assessment can be developed (Ross, 2000). Consequently GIS applications have increasingly become an integral component of natural resources management activities worldwide (Nath *et al.*, 2000).

As described by Ross (2000), the power of GIS is the ability to draw together the many diverse and complex factors, which may need to be considered to reach development and administrative decisions. Likewise, GIS has a number of attributes, which suit it to detailed modelling for fishery management and site selection for aquaculture operations.

A number of studies on fisheries management and aquaculture potential have been developed using relatively simple environmental and resource availability models (Long *et al.*, 1994; Kapetsky, 1994; Kapetsky and Nath, 1997; Aguilar and Nath, 1998). In addition to this, GIS models based on environmental and system considerations have been shown to be an excellent tool for detailed facility location, once a preliminary choice of site has been made (Ross et al., 1993). These techniques have been applied in both developing and developed countries, and to both coastal marine and inland fresh water fisheries.

More recently, these GIS applications have been extended to assess lease site selection for aquaculture growth-out of benthic shellfisheries of commercial importance (Arnold *et al.*, 2000). In this context, various studies have recognised the need to consider multiple factors when determining the site suitability for aquaculture of benthic resources (Krieger, 1990; Berrigan, 1996).

4.2 OBJECTIVES

The aim of the GIS- based modelling component developed in this research was to create a systematic and logical procedure for determination of the potential for restocking sea urchins within given coastal areas, considering the subtidal and intertidal zone. This was carried out through the identification, quantification and selection of potential sites for restocking *Loxechinus albus* juveniles within the study area (AMEBRQ). Simultaneously, the work aimed to develop a standardised methodology for the generation of a GIS database from the cartographic information and resource assessment data usually provided in the Base Line Study (BLS) within the framework of Areas of Management and Exploitation of Benthic Resources (AMEBRs) in Chile.

To address these issues, the major objectives of this chapter were defined as follows:

- To generate a GIS database and develop a geographical representation of the relevant physical environment concerned with this study.
- To develop a geographical representation of the characteristics describing major natural stocks of other relevant benthic resources ("loco"- abalone and key- hole limpets) coexisting in the AMEBRQ.

- To develop a geographical representation of the characteristics describing major natural stocks of the red sea urchin in the AMEBRQ.
- To identify and quantify suitable restocking areas taking into consideration the specific requirements of the species as well as operational factors associated with a sea urchin restocking exercise.
- To determine the effective available area within the areas identified as suitable and to propose potential sea urchin restocking sites within the study area.

4.3 MATERIAL AND METHODS

4.3.1 GIS SOFTWARE AND HARDWARE

The geographic information systems- based restocking model was developed using Idrisi32 for Windows. This covers the full spectrum of GIS and Remote Sensing needs from database query, to spatial modelling, to image enhancement and classification. Special facilities are included for environmental monitoring and natural resource management, including change and time series analysis, multi-criteria and multi-objective decision support, uncertainty analysis (including Bayesian and Fuzzy Set analysis) and simulation modelling (including force modelling and anisotropic friction analysis).

Complementary spatial- drawing and digitising software such as AutoCAD14 and CartaLINX was also used during the data input stages of the spatial modelling. This was specifically used for data import and on- screen digitising procedures, depending on the format of the primary cartographic data.

As for the bio-socio-economic modelling stage, the GIS- based work was entirely undertaken at the GISAP of the Institute of Aquaculture, using both computing systems and infrastructure available at this laboratory (for details refer to Chapter 3).

4.3.2 CRITERIA CONTROLLING SITE SELECTION IN COASTAL RESTOCKING EXERCISES

The first stage of this work was to identify the major criteria that may influence site selection for development of an onshore coastal restocking exercise of sea urchins.

Criteria, or factors, controlling the development of a farming activity are defined as production functions (Meaden and Kapetsky, 1991). These factors (economic, social, biological, environmental, technical, etc.) interact to form complex dynamic systems, in which a number of processes regulate and determine the success or failure of any productive activity based on them. Many of these production functions can be geographically referenced, which means that their existence and behaviour can be referred to a specific geographic location.

No universal technique is available for the definition of the correct set of criteria, and hence the selected set will depend on the system and conditions of study. Therefore production functions must always be referred to the specific research problem and, the number of factors regulating an activity is directly related to the complexity of the problem studied. As a result, the type and amount of required and available information for tackling a particular decision problem is related to its complexity (Massam, 1993).

Identification, analysis and selection of factors has been done using a range of methodologies, including literature reviews, systems analysis, and experts opinion. For this study, identification and selection of criteria was undertaken by a comprehensive analysis of the case study (AMEBRQ). This was done in conjunction with the use of the expertis opinion provided by the MRCQ staff, technical unit of the fishing association and local fishermen at Quintay.

As it is not always possible to examine and describe all the factors influencing a given activity in a system, the methodology of this study was based on the following steps:

- identification of all potential major criteria,
- evaluation of the degree of influence and variability of each factor,
- determination of potential for manipulation of each factor,
- quantification of available related information, and finally
- selection of essential criteria.

Following these steps, criteria were aggregated in groups according to the nature of their influence in the system. A factor can be defined as a production function that enhances or detracts from the suitability of a specific alternative for the activity in consideration (Eastman, 1993). The same factors can be used in different ways depending on the point of evaluation for the activity. Thus, for example a given depth may increase the suitability of a given site for cage aquaculture based on technical specifications, however the same depth may at the same time decrease the site' s suitability because of high current velocities. Some factors were used in each of the three groups generated, due to their effects across several applications and model components. Final groups of factors identified and selected are listed in the Table 4.1.

Table 4.1: Groups of factors for site selection in restocking sea urchins in Chile.

Groups		**Factors**	
1.	Species requirements	i.	Bathymetry[1]
		ii.	Seabed type
		iii.	Coastline exposure[1]
		iv.	Red sea urchin natural stocks distribution
2.	Operational factors	i.	Bathymetry[2]
		ii.	Coastline exposure[2]
		iii.	Accessibility by land
		iv.	Accessibility by sea
3.	Area availability	i.	Available area inside sea urchin natural stocks
		ii.	Available area inside keyhole limpets natural stocks
		iii.	Available area inside loco"-abalone natural stocks

The first group of factors are biotic and abiotic elements, which interact in highly variable, dynamic and complex systems such as the intertidal and subtidal coastal zones. These factors are species specific and their combination determines the life-stage's natural distribution. For this reason, these criteria were used in terms of the species requirements to identify suitable habitat for development in open natural environments.

The second, but also important, group is formed by those technical practicalities associated with the restocking exercise itself. Thus, mass restocking programmes for benthic resources involve several activities, land-based and aquatic, each with important physical constraints. Operational factors are considerable and can eventually determine the success or failure of a restocking practice. Hence, the combination of these criteria was used to estimate the feasibility for restocking in a given site.

The last group of criteria relates to the actual area to be used for restocking. Thus, even if a given coastal lease may be highly suitable and technically feasible for restocking sea urchins, its effective area may be limited by the natural distribution of wild stocks of the same or other benthic species. Considering the relevant ecological interactions (competition for substrate, food resource, predation, etc), a successful restocking programme must avoid, if possible, any conflict, overlapping and intervention on natural fisheries occurring in the target area. This is even more relevant when dealing with benthic species (red sea urchin, and gastropod molluscs), which strongly rely on the substrate for vital functions, such as larval settling, metamorphosis, juvenile development, feeding, etc. As a result, the spatial coverage of natural resources in the coastal area is essential to estimate effective area availability for realistic implementation of a restocking programme.

Final combination of these groups, allows the identification, quantification and selection of suitable, feasible and available sites for sea urchin restocking within the coastal lease studied.

4.3.3 DATA SOURCES AND INPUT PROCESS

Successful decision-making relies on the quality and quantity of information available. Development of GIS models requires an important amount of good-quality data. Data could be classified in two major categories- primary and secondary data. The first refers to field-collected data such as water temperature or resource distribution, and the second to processed information, as for example: paper maps.

Data quality and quantity are common limiting factors for a GIS system. Available data will be, most of the times, of different coverage, period, scale, resolution, etc. For this reason, the GIS modeller is forced to adopt special methodologies to gather primary and secondary data needed. For this study, a variety of sources were used to the gather data for input into the GIS system, with a range of input procedures and techniques to enter this information into the GIS database that are developed in the next sections.

Cartography

Cartography is the most important primary data used for the GIS model. General terrestrial cartography of the study region was acquired from the Military Geographic Institute, Chilean Army. This is the only official source of maps covering the Chilean territory in a scale, of 1:250,000, 1:50,000 and 1:25,000. The following maps (Table 4.2) were bought in paper format from the central library at Santiago, Chile.

Table 4.2: Specifications of the general cartography data sources.

Manufacturer	Code	Area covered
Instituto Geográfico Militar (IGM)	1. Valparaiso, Chart IGM E- 47 5-04-05-0047-00	33° 00'- 71° 30'
" "	2. Algarrobo, Chart IGM E- 54 5-04-05-0054-00	33° 15'- 71° 30'
" "	3. Valparaiso, Chart IGM 1220	33° 37'- 71° 37'
" "	4. Quintay, Chart IGM 1221	33° 07'- 71° 37'

Note: all paper maps on scale 1: 50,000, 1st Ed. year 1994.

An aerial photograph of the study area (Fig. 2.4, Chapter 2) was also used to create the background base map for inserting the output layers of the GISRM, offering a more realistic overview of the region. This digital data was of exceptional image quality, allowing several levels of zoom-in and showing terrestrial and coastal features in great detail. This image was directly acquired from the supplier at Cerrillos Airport, Santiago, Chile (Table 4.3).

Table 4.3: Specifications of the aerial photograph of study region.

Manufacturer	Code	Area covered	Scale	Resolution	Year & edition	Format
Servicio Aéreo Fotogramétrico	024268	From Long Beach of Quintay to Punta Tunquen	1: 20,000	800 dpi	1994 1st Ed.	Bitmap image (*.bmp), stored on 1 CD

Finally, high-resolution (≈1m) digital cartography (Table 4.4) was obtained from the Base Line Study developed at the Area of Management and Exploitation of Benthic Resources of Quintay. This work was supervised and partially developed by a private cartographic surveillance consultant company, and based on several localised inland, coastline and near-shore surveys of the study area. A qualified working team undertook direct surveys covering more than 150 ha during 1999, where the AIAFQ and the MRCQ provided equipment and labour force for this process.

Table 4.4: Specification of the digital cartography relevant to the AMEBRQ.

Attributes	Features
Study area boundary	Vector polylines
Bathymetric curves	Vector polylines
Seabed type: Rock; Sand, and Balls	Vector polylines
Benthic resources substocks geographic distribution: Red sea urchin; 'Loco'- abalone, and Keyhole limpets	Vector polylines
Sampled transects geographic location	Vector lines

Note: all Compressed AutoCAD14 files (*.dwg) stored on 3½ floppy disks and paper copy. Area covered: AMEBRQ (103 Ha); Scale: 1:2,000; Resolution: 1.3 m, and manufactured by Rojas, H. Cartographer in 1999.

Benthic resources population data

Population data constituted the major source of information for the construction of the benthic resource GIS databases, including the red sea urchin, "loco"-abalone and keyhole limpet species. This information was extracted from the Base Line Study undertaken at the AMEBRQ, and then processed through the GIS database generation stage. The data was obtained at no cost directly from the fishermen's association who collaborated with the working group at the MRCQ at Quintay Bay during the first fieldwork stage. Key contents of this report are described in detail in Chapter 2. Table 4.5 lists the population attributes covered in this resource assessment.

Table 4.5: Benthic resource's data specifications.

Resource	Population attribute	
1. Red sea urchin	i. Major patch zones or substocks	vii. Mean density per sampled patch zone
	ii. Abundance per sampled patch zone	viii. Overall size frequency distribution
	iii. Total estimated population	ix. Relation test diameter-weight
	iv. Estimated exploitable stock	x. Potential inhabitable area
	v. Estimated juvenile stock	xi. Effective patching area
	vi. Estimated seed stock	
2. "Loco"-abalone & keyhole limpets	i. Major patch zones or substocks	v. Overall size frequency distribution
	ii. Total estimated population	vi. Relation weight-length
	iii. Total estimated biomass	vii. Estimated total permissible capture
	iv. Mean density per sampled patch zone	

Note: Resolution: 1 m; Format: Excel spreadsheets & graphics.

Scoring and weighting input data for the model

Input data required for database manipulation and suitability modelling stages was obtained through four sources of information:

- author's knowledge of the system,
- mathematical approach,
- review of relevant literature and specific reports, and
- inquiry with specific experts.

Here, the use of questionnaires, either with personal interviews or Email communications, was an important tool for acquisition of scientific and technical data required for modelling the system. Special questionnaires were designed for this purpose (see Appendix 1) and a group of agents were selected and contacted for its completion.

On-screen digitising

Digitising is the process of encoding analogue data (hardcopy maps or graphics) into digital format. However, when data is already in digital format, on-screen digitising can be used to select and isolate specific features of interest from a map, figure or any image displayed on the computer monitor.

In this study most of the images used were imported into IDRISI32 in digital format, and on-screen digitising was used to isolate specific features, such as roads and buildings, from scanned paper maps. This was done using the DIGITIZE module available in IDRISI32, by which points, line, polygon and text vector layers may be created. To digitise on-screen, a layer in a map window must be displayed. This layer may be raster or vector containing one or several layers and will define the reference system and coordinates for the digitised features. Thus, a new vector layer could be created or features could be added to an existing vector layer through on-screen digitising.

Scanning

Scanning was used out in order for acquisition of several images from paper maps and photographs, using a Hewlett Packard (Hp Scanjet 3c) flatbed scanner along with the Deskscan III v.2.8 supporting software.

Likewise, the aerial photograph produced by Servicio Aereo Fotogrametrico must be included as an important information resource of excellent quality and detail.

Further detailed explanation regarding the manipulation and treatment carried out while importing this data into IDRISI32 is given in following sections of this chapter.

4.3.4 DATABASE GENERATION, MANIPULATION AND SCORING

Once the criteria were selected and data sources were gathered, these factors were represented by means of thematic maps, making up the GIS database. Thematic layers were therefore generated by the following manipulation procedures:

- importation,
- georeferencing, and
- further manipulation routines (interpolation, reclassification, overlay, scalar, distances).

Subsequently, final thematic maps describing each criterion were scored to a common system. This made it possible to integrate different sources of data, measured in different units and scales.

Importation

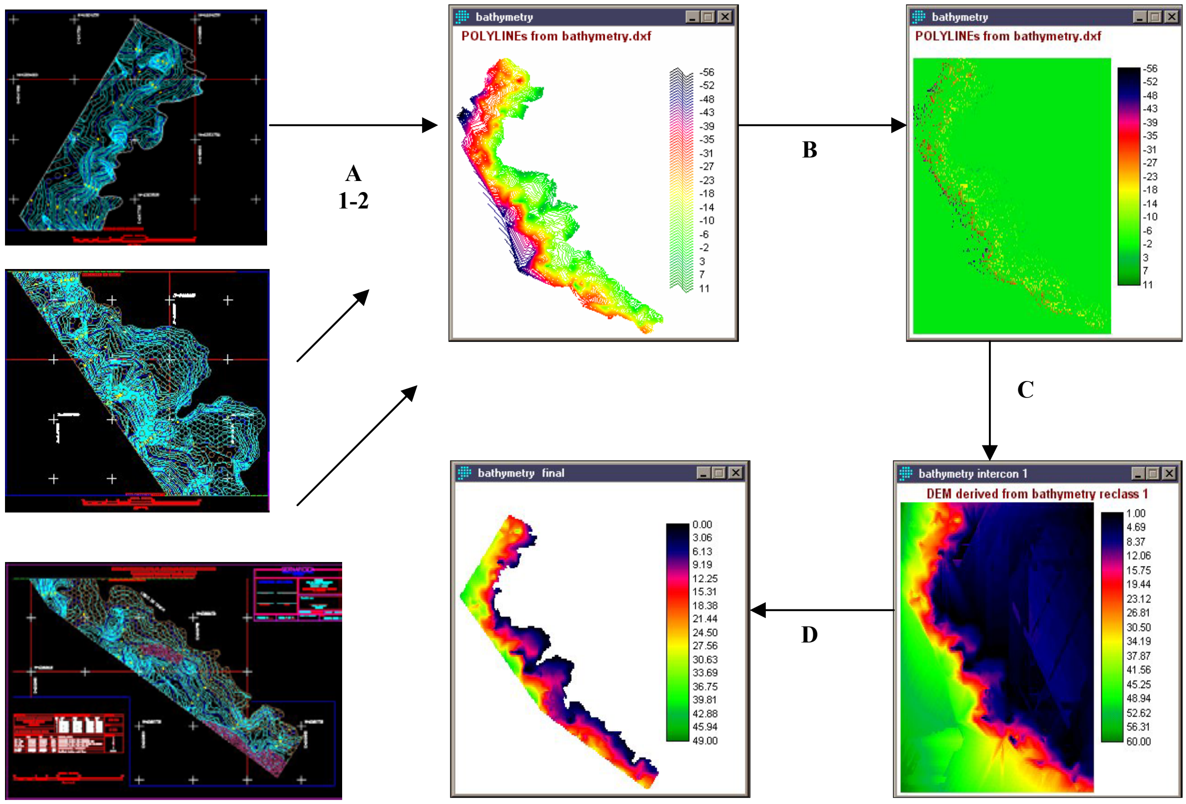
Some digital images used for this study were available in AutoCAD14 format (*.dxf). These were imported using the format-specific tool in IDRISI32, so as to retain the most important characteristics of the original images such as the features and associated polygon and line vectors, but more importantly to the original scale, resolution and geographic reference of the maps describing the study area.

Likewise, relevant bitmap files, such as the base background photograph and few scanned paper maps, were also imported into IDRISI32. This preliminary treatment allowed the generation of fully compatible IDRISI32 raster image files forming the basic thematic maps in the GIS database. The processing sequence is shown in Fig. 4.1.

This process resulted in a number of intermediate and final output files for each source map. Detailed specification of these files is given in Table 4.6.

Georeferencing

Since most of the maps were imported into IDRISI32 conserving their geographic reference, only limited georeferencing was needed in very specific cases (photographs and scanned paper maps). These images had a plane reference system by default and this was reprocessed using the module RESAMPLE, available in IDRISI32. These images were therefore corrected to the standard reference system of the original imported digital projections (UTM-19S).



A.1: Generation of CARTALINX coverage (*.lnx) files by aggregation of map sections and import AutoCADR14 (*.dxf) files into IDRISI32 and then to CARTALINX for generation of polygons or line (*.lnx) vector files.

A.2: Generation of IDRISI32 vector (*.vct) files by importation of CARTALINX coverage (*.lnx) files into IDRISI32.

B: Generation of IDRISI32 raster (*.rdc) files by vector (*.vct) to raster (*.rdc) file conversion (POLYRAS-LINE)

C: Generation of DEM raster surface, using surface interpolation (INTERCOUN) (for bathymetry)

D: Clearance of non- study area by mask application and further image processing

Figure 4.1: Preliminary manipulations carried out with digital cartography.

Table 4.6: Specifications of image files and final layers resulting from preliminary treatment.

File/ Layer	Source	Type
CARTALINX coverage files (*.lnx)	AutoCADR14 vector files (*.dxf)	Vector polygons
IDRISI32 vector files (*.vct)	CARTALINX vector files (*.lnx)	Unclassified vector polygons
IDRISI32 raster files (*.rdc)	IDRISI32 vector files (*.vct)	Unclassified raster polygons and lines
IDRISI32 raster files (*.rdc)	IDRISI32 raster files (*.rdc)	Classified raster polygons and contour surfaces

Note: Scale: 1:2,000; Resolution: 1.3 m; Features: study area boundary, bathymetry, seabed, geographic distribution, and natural substocks benthic resources.

Scoring

Although the attributes of an object (e.g. image or map) can be measured using many different scales, multicriteria evaluation requires that units describing each criterion should be common, standard, and commensurate. This allows classified maps to be combined, and to obtain a measurable output in a known standard scale. Hence, each criterion-base map must be transcribed into standardized units of evaluation, defined as a *scoring system*.

The scoring system used for this study was based on a 10-point scale, where 10 is the most suitable and 1 the least (Table 4.7). Similar studies have used different scoring systems varying from 1 to 4 (Salam, 2000), 1 to 8 (Perez-Martinez, 2002), and up to 1 to 16 (Aguilar-Manjarrez, 1996). Short scoring systems tend to give poor results while long scoring systems are too complicated to use. Using a ten-point scale, as a derivation of a percentage scale (0% to 100%) provided an intuitive, easy to use, understandable, and adequately descriptive system.

Table 4.7: Scoring system.

Score (measured in points)	Percent scale correspondence (0% to 100%)	Description
1	between 0% and 10% suitability	Most unsuitable
2	between 10% and 20% suitability	Unsuitable
3	between 20% and 30% suitability	Marginally unsuitable
4	between 30% and 40% suitability	Poorly suitable
5	between 40% and 50% suitability	Medially suitable
6	between 50% and 60% suitability	Moderately suitable
7	between 60% and 70% suitability	Fairly suitable
8	between 70% and 80% suitability	Suitable
9	between 80% and 90% suitability	Very suitable
10	between 90% and 100% suitability	Most suitable

Scoring of a thematic layer could be based on a simple mathematical operation, personal opinions from an expert, or taken from relevant literature. Scoring can also be linear or non-linear. The appropriate strategy is determined by the criterion to be measured and the quantity and quality of available information. Hence, mathematical approaches will be the only way when no other information is available to set threshold values (Barredo, 1996; Malczewky, 1999), while when expert opinion is available, the best strategy will be to define threshold values based upon their knowledge on the activity proposed for the particular study area. Literature reviews have also been an important source of information for establishing scores.

Threshold values for this study were defined using an integration of the three methodologies previously mentioned. Thus, each criterion was separately analysed, scoring strategy defined, and thresholds set, using the following approach:

- *high-technical criteria* (e.g. water temperature for carp aquaculture): based on expertise, specific questionnaires and relevant literature,
- *low-technical criteria* (e.g. specific markets for the product): based on common knowledge of the author and working group at the GISAP laboratory, and
- *unavailable-data criteria* (e.g. distance to markets for product commercialisation): based on mathematical calculations and logical analysis of the problem.

4.3.5 GIS MODELLING

The conceptual structure for modelling restocking site selection was constructed using hierarchical order structures. These structures allow the modeller to divide the system, and then aggregate modelling factors into smaller units or submodels (Malczewski, 1999).

After the conceptual hierarchical structure was defined, preferences were set by means of weighting the criteria integrating submodels, according to their importance in the subsystem. Finally, scored and weighted criteria maps were integrated using decision rules, the resulting output being a combination of the scores and weights of all criteria defined for each submodel.

Hierarchical structure

Hierarchy analysis implies the study of order between partitions (levels) in a given structure. Hierarchical structures allow division of criteria into clusters and their subsequent subdivision into smaller clusters, and so on. Thus, is possible to establish orders of priorities between structural elements, generating levels of hierarchy to deal with rather than treat all the elements together. The number of levels and clusters integrating them are defined by the modeller, and its grouping will vary according to the nature and connection of the elements in relation to the function they perform or property they share (Saaty, 1988).

The hierarchical structure for the site selection for restocking sea urchins in Chile is presented in Fig. 4.2. Here, the top level represents the final goal of the multicriteria decision-making analysis process. The intermediate level refers to the submodels, which were weighted, and then combined to generate the final output map. Finally, the third and bottom level describes all criteria identified, selected, generated and scored according to their influence in the goal of study.

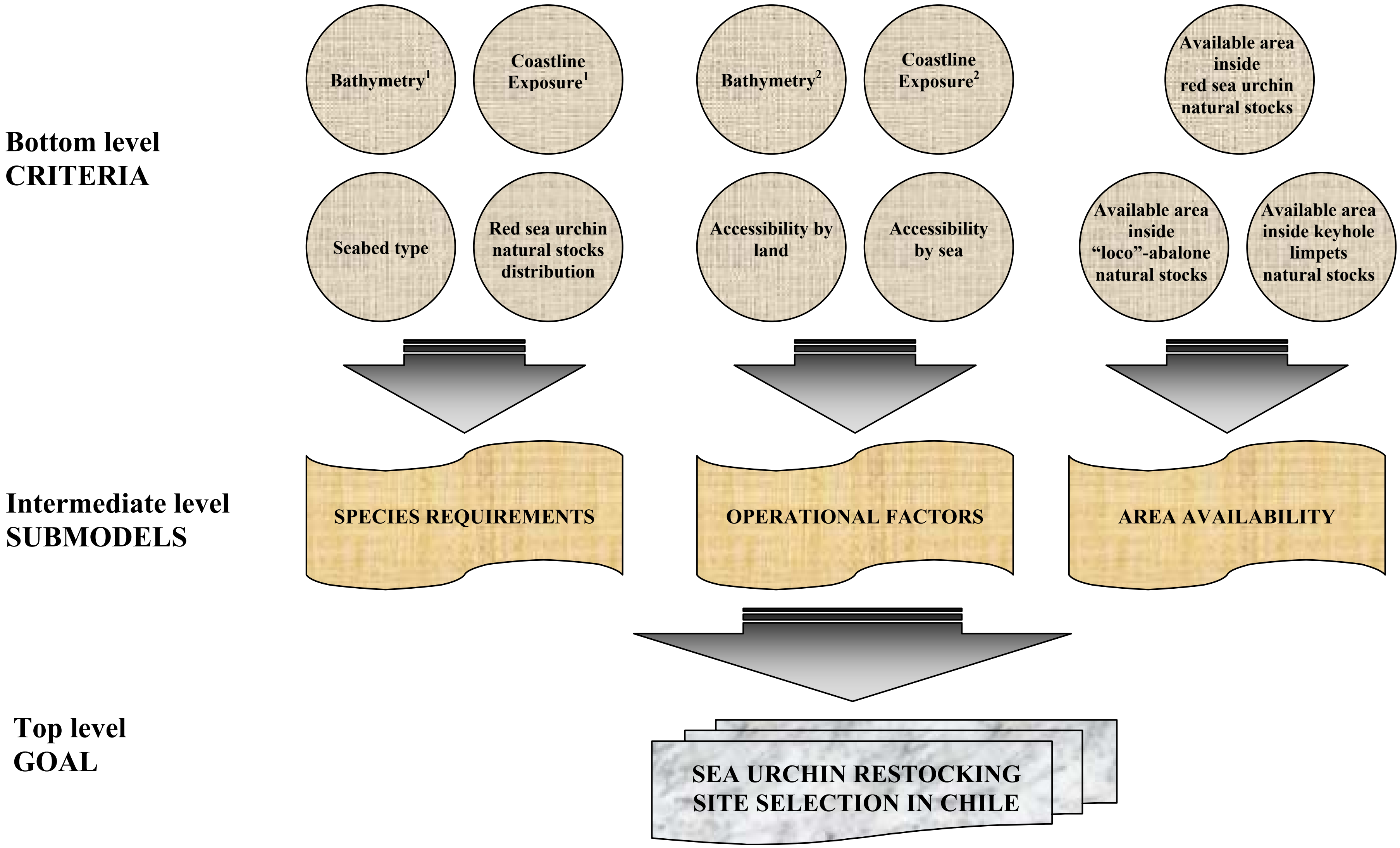


Figure 4.2: Hierarchical structure of the suitability analysis for sea urchin restocking site selection in Chile.

Criterion weighting

Weights are assigned to criteria in order to reflect the importance of each criterion in relation to the others. Most systems usually normalize weights to sum to 1 (100%), where the weight magnitude determines the relative importance of criteria.

Several weighting procedures based on the preferences set by decision-maker have been proposed in Multi Criteria Evaluation (MCE) literature, including ranking, rating, pairwise comparison and trade-off analysis (Barredo, 1996; Malczewski, 1999). Choosing the correct method for weighting criteria relies on the ability to balance required accuracy, practical use and understanding, software capabilities and the methodology for incorporating of this information into the GIS database.

Taking into account the relatively small number of criteria selected (maximum of 4 in each of 3 submodels) a direct percent rating was adopted as a *weighting system*. This allowed the decision-maker or modeller to decide weights for criteria, and for submodel combination, in terms of percentages based on a 0% to 100% scale. These, values were then expressed as decimals allowing direct input into the MCE module used in IDRISI32.

Percent ratings used on each criterion and submodels final combination were estimated by means of questionnaires, and personal interviews with experts specifically selected based on their background and subject knowledge.

Decision rules

Once criteria were defined and decision-maker preferences set up in the spatial multicriteria decision analysis, the final stage was to combine and integrate these elements using decision rules, and the process of MCE.

From the many decision rules available in the MCE methodology, this study used the *weighted linear combination* (WLC), which is the most often used in spatial multicriteria evaluation. This is based on a *weighted average,* whereby the modeller assigns weights of importance to the various factors. Using these weights, each scored factor is then multiplied and finally summed to give the weighted average (Fig. 4.3). To achieve this IDRISI32 provides a built-in module, MCE, which allows for multicriteria evaluation using the WLC methodology.

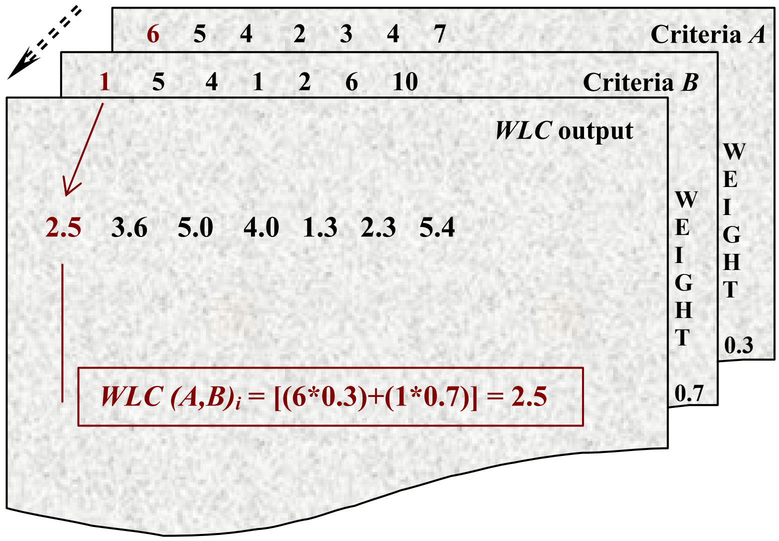


Figure 4.3: Example of the weighted linear combination method (redrawn from Barredo (1996))

4.4 Results

4.4.1 The AMEBRQ GIS database

Study area boundary, bathymetry and seabed composition thematic maps

Three thematic maps comprised the GIS database describing the physical characteristics of the study area.

- study area boundary (Fig. 4.4),
- bathymetry (Fig. 4.5), and
- seabed (Fig. 4.6).

The study area covers a limited coastal area of 104 Ha (Fig. 4.4). The lease area ranges in depths from 0 to 50-m, and the bottom is mostly characterised by a large rocks throughout both the subtidal and intertidal zones (Fig. 4.5 and 4.6).

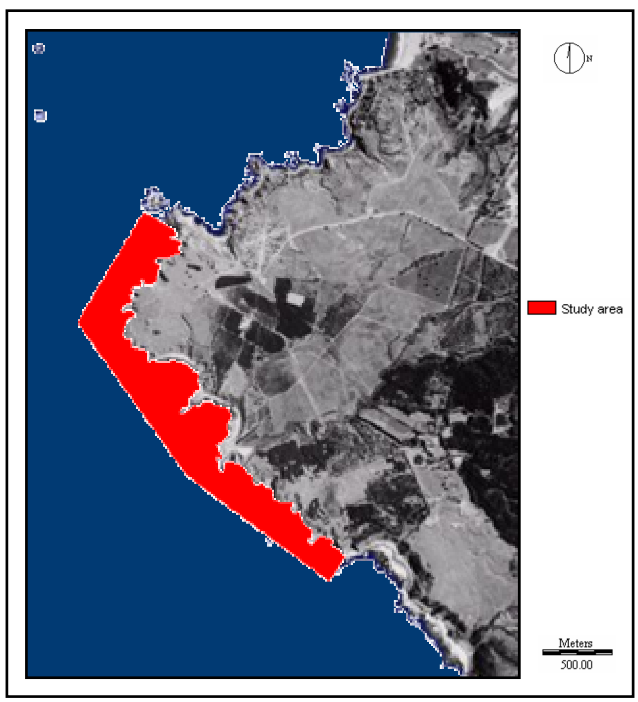


Figure 4.4: Boundary of the study area.

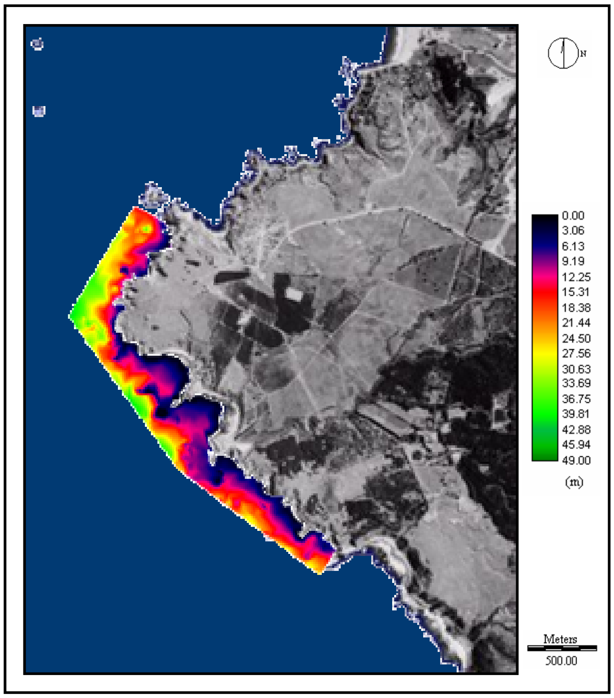


Figure 4.5: Bathymetry of the study area.

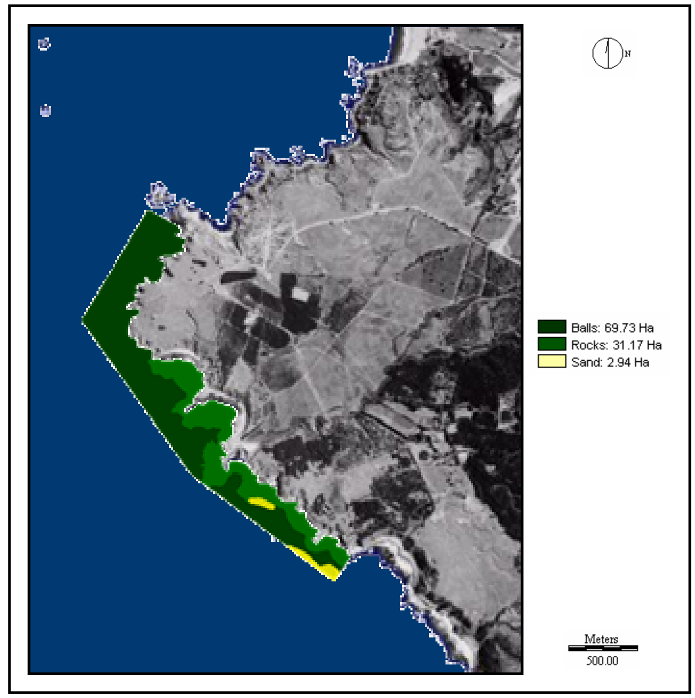


Figure 4.6: Seabed composition of the study area.

Red sea urchin thematic maps

Six thematic maps were generated, describing the state and distribution of the natural substocks of red sea urchin in the study area. This data comprised:

- major substocks (Fig. 4.7),
- population distribution (Fig.4.8),
- mean density (Fig. 4.9),
- potential inhabitable zone (Fig. 4.10), and
- effective coverage (Fig. 4.11).

As shown in Fig. 4.7 the red sea urchin is distributed in nine, very delimited major substocks in the study area. However, only 6 of these were selected for the resource evaluation undertaken during the Base Line

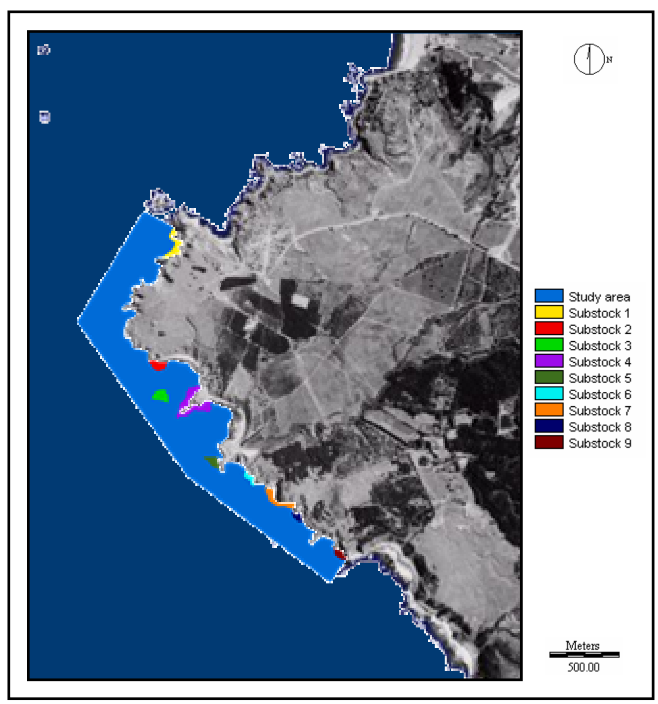


Figure 4.7: Red sea urchin major natural substocks.

Study in 1999, as they were the major patches. Therefore all the following thematic layers refer only to those substocks selected and sampled (substocks 1 to 5 and substock 7)

With an overall estimated population of 452,775, the largest group of 192,033 individuals is the substock 7 and the smallest the substock 5 with 9,936 sea urchins (Fig. 4.8).

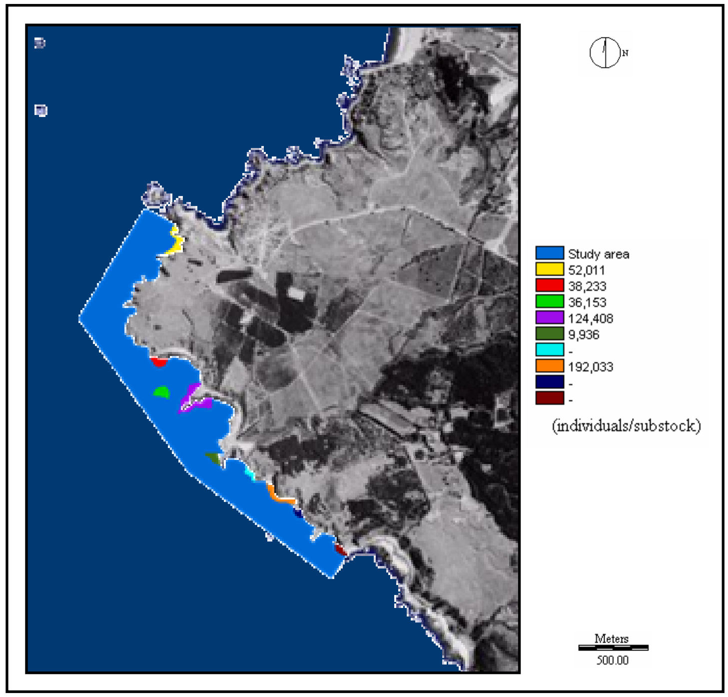


Figure 4.8: Red sea urchin population distribution.

The mean density of sampled substocks is highly variable within the population studied, varying between 4.8 and 58.86 individuals/m^2 (Fig. 4.9).

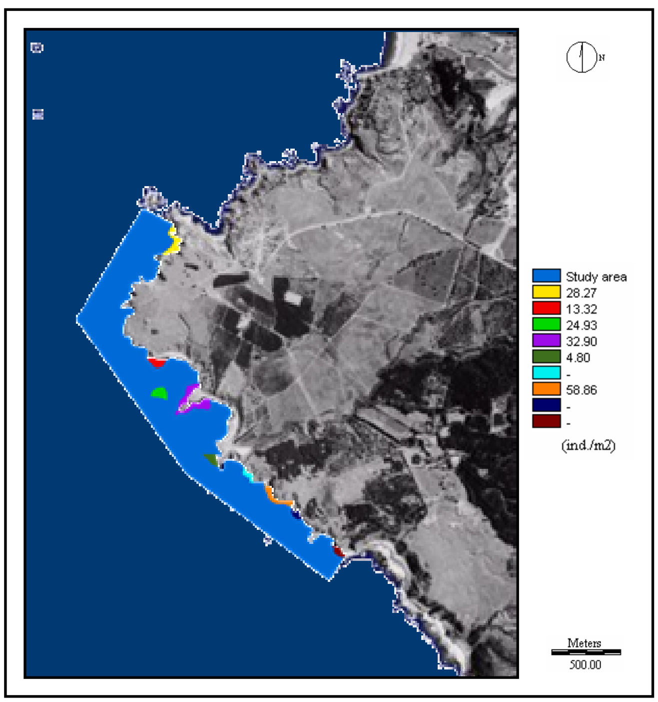


Figure 4.9: Red sea urchin mean density.

The potential inhabitable area for red sea urchins (Fig. 4.10) was determined on the basis of the contiguous area to each patch and the optimum depth for the species. On the other hand the effective coverage (Fig. 4.11) corresponds to the actual size of each patch or substock which was directly estimated by divers during the sampling procedure.

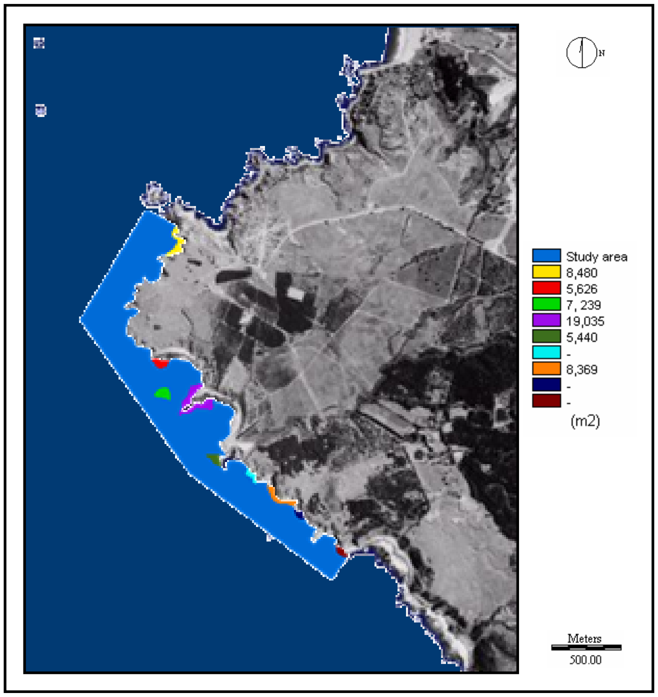


Figure 4.10: Red sea urchin potential inhabitable area.

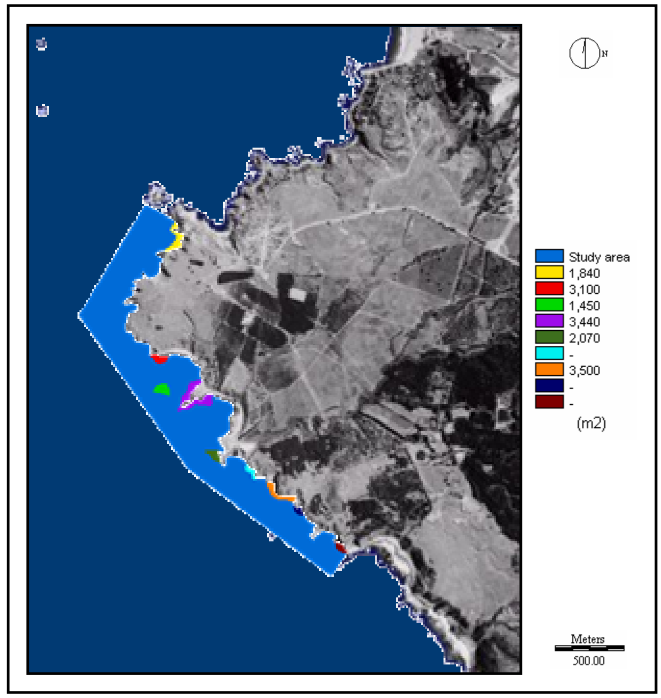


Figure 4.11: Red sea urchin effective coverage.

Thematic maps of other benthic resources

Two thematic maps, were generated describing the geographic distribution of natural substocks of the keyhole limpet (Fig. 4.12) and the "loco"-abalone (Fig. 4.13). These species have very few important substocks in the study area. However all of these natural banks are significantly larger than the total area of sea urchin substocks.

Finally, considering all benthic resources assessed, a summary thematic map was created showing the overall distribution of major substocks (Fig.4.14).

Major banks of commercial resources in the study area are distributed very discretely. There are very few zones where the species coexist.

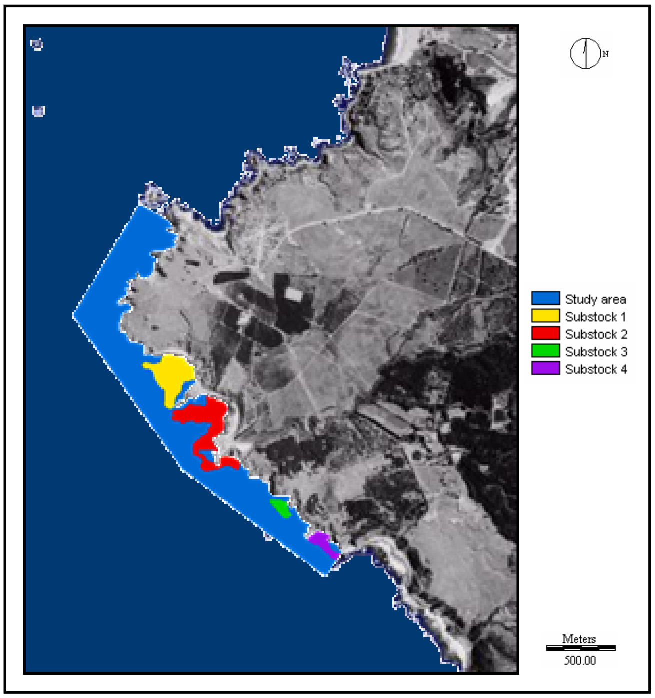


Figure 4.12: Keyhole limpet major substocks.

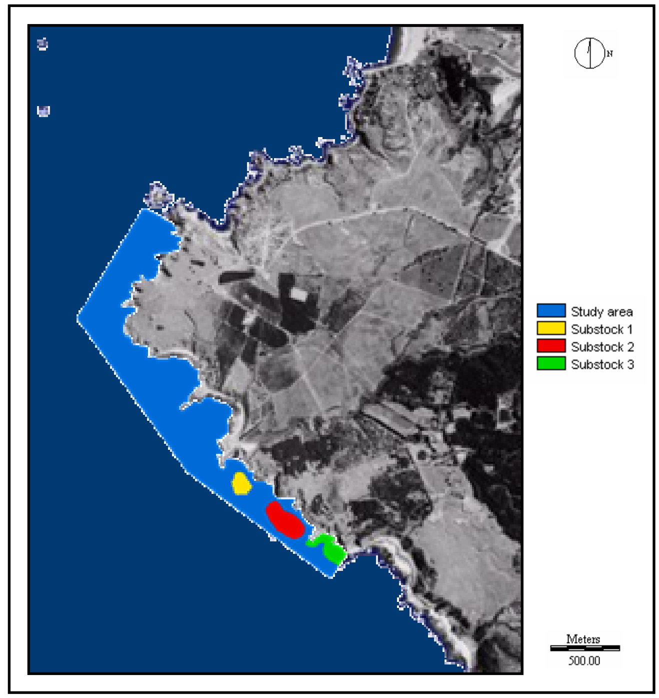


Figure 4.13: Distribution of "loco"-abalone major substocks.

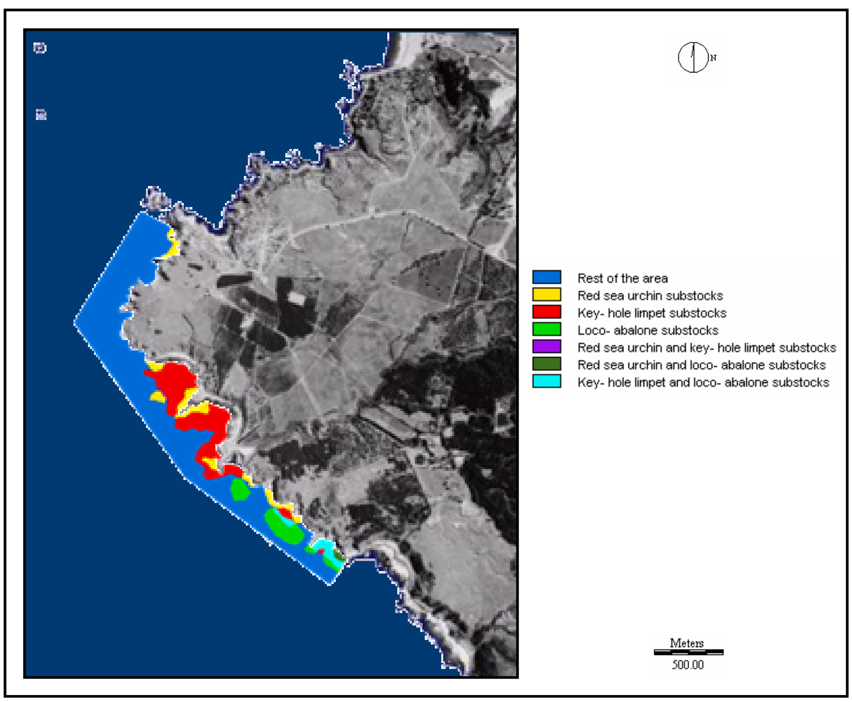


Figure 4.14: Major benthic resources overall distribution.

4.4.2 SPECIES REQUIREMENTS SUBMODEL

Bathymetry[1]

Vertical distribution of sea urchins is determined by a number of biotic and abiotic factors. Among the latter, water depth is clearly one of the most important factors, and so it can be effectively used to define suitable areas depending on the species-specific requirements.

The red sea urchin *Loxechinus albus* is widely distributed from the intertidal zone to 340 m depth (Bernasconi, 1953; Larrain, 1975), but commercial fisheries are mostly exploited at depth up to 40 m (Arias and Bustos, 1991). Likewise, individual life-stages have differential requirements, and therefore subpopulations aggregate at different depths covering the intertidal and subtidal coastal zone (Castilla, 1990). Hence, this species shows migratory patterns from intertidal to subtidal zones as it settles, transforms into a juvenile and finally reaches the commercial adult size (Fig. 4.15). Given that early juveniles would prefer exposed shallow intertidal pools as migratory starting bases, a restocking strategy should be based on this natural behaviour, and use these sites as dispersion points to other coastal areas (Stotz *et al.*, 1992).

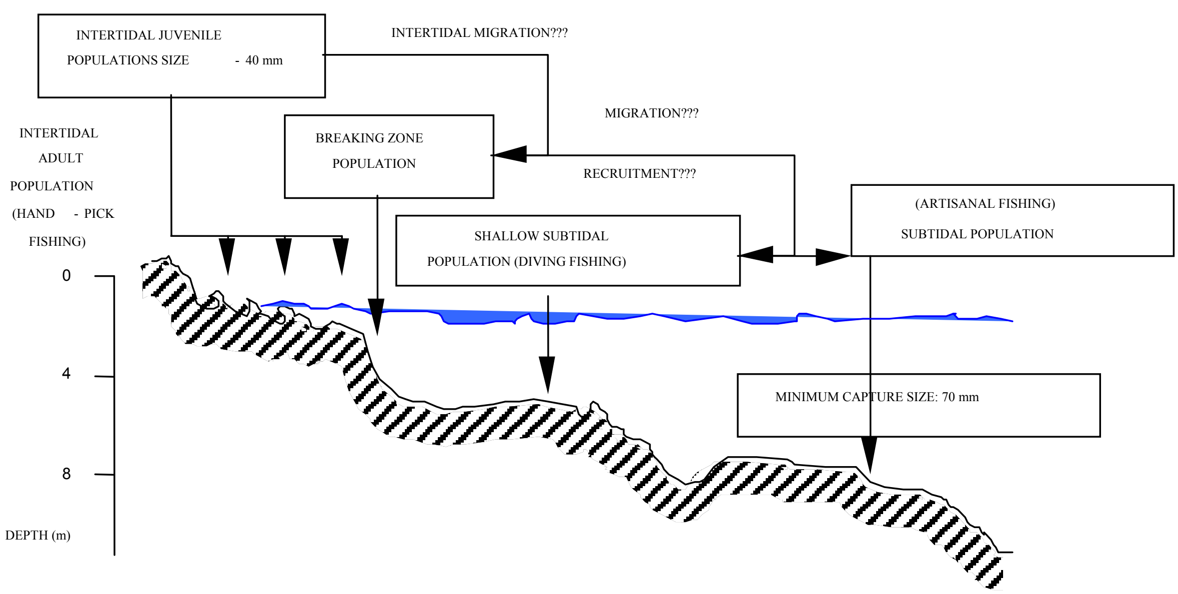


Figure 4.15: Vertical distribution of the red sea urchin *Loxechinus albus* (Modified from Castilla (1990))

Having established the relevance of bathymetry for restocking site selection, depth thresholds were obtained based on expert opinion derived from questionnaires and interviews with experts of varied biological-ecological and aquaculture-fisheries science backgrounds. Based on this data, final threshold values were selected (Table 4.8) and the bathymetry thematic map was reclassified using the module RECLASS. Figure 4.16 shows the output suitability map for bathymetry of the study area.

Table 4.8: Depth threshold values used for bathymetry based on the vertical distribution of the species.

Score	Criteria	Bathymetry (m)
1		-
2		30- >50
3		-
4		25-30
5		20-25
6		-
7		15-20
8		1-5 & 10-15
9		-
10		5-10

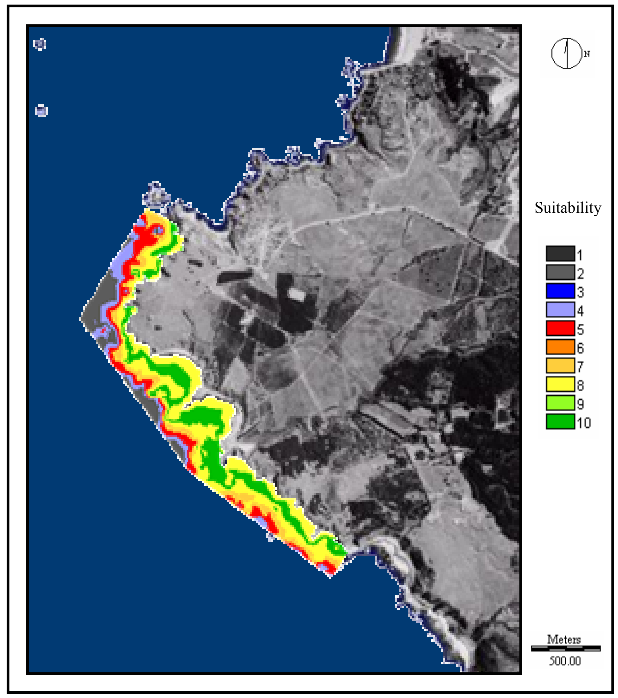


Figure 4.16: Suitability map for bathymetry based on the vertical distribution of the red sea urchin.

Seabed type

Type and condition of local substrate is also a very important abiotic factor, which determines amongst other things, recruitment, growth and general development of echinoids (Birkeland and Mesmer, 1978; Lang and Mann, 1976). This habitat requirement can be related to the particle composition of the substrate, as well as other characteristics, such as its algae coverage or morphology. A good example of this was shown by Fuji and Kawamura (1970), who reported significant differences in subtidal recruitment density of *Strongylocentrotus intermedius* in Hokkaido. Here, the highest concentration of newly settled animals was on a cobble (<30-cm diameter) bottom, whereas adults were found in habitats with boulders (>50 cm).

The Chilean red sea urchin naturally inhabits harsh-stony substrates, mainly rounded boulders of rocky seabed, and also ball-type rocks and gravel (Bustos *et al.*, 1991). This substratum provides an irregular three-dimensional surface favouring larval settlement during recruitment. This type of substrate favours the development of diatoms, microalgae and calcarean algae, all of which are important induction agents of marine benthic resources metamorphosis (Hahn, 1968; Kawamura, 1984; Morse *et al.*, 1979). This substrate is also an optimal refuge, offering protection from predators, and increasing survival (Bustos *et al.*, 1991). Finally, adults become strongly attached to rounded boulders and ball-type rocks in high- current and turbulent zones where they catch drifting algae, on which they feed. By contrast, sandy and/or mud substrates, composed of small-size particles can enter the ambulacral podia; constrain their functions, attachment to the bottom, and therefore their natural development.

Based on this and additional information gathered with local fishermen and divers, thresholds were defined (Table 4.9) and the seabed thematic layer was reclassified using RECLASS. Fig. 4.17 shows the output suitability map for seabed of the study area.

Table 4.9: Thresholds used for seabed composition.

Score	Criteria	Seabed
1		-
2		Sand
3		-
4		-
5		-
6		-
7		-
8		-
9		Balls
10		Rock

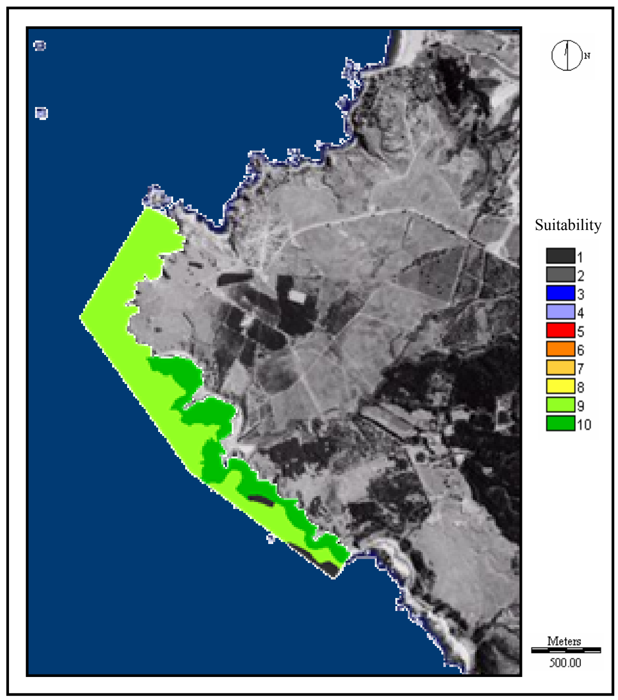


Figure 4.17: Suitability map for seabed.

Coastline exposure[1]

Together with bathymetry and seabed composition, coastline exposure is the third, and possibly the most relevant, abiotic factor regulating the distribution and development of the red sea urchin *L. albus* (Bustos *et al.*, 1991). This applies to most benthic resources of commercial interest in Chile, such as “loco”-abalone and key-hole limpets, which mostly inhabit highly windy and wave-exposed areas in the North and Central coast (Barbieri and

Silva, 1996). Consequently, these areas represent the most suitable sites for restocking of benthic resources.

Stotz *et al.* (1992) reported from experimental restocking studies that although there are a number of determinant biotic and abiotic factors, the most significant and positive relationship to permanency and survival of restocked juveniles is wave exposure in shallow pools. This positive relationship has been shown primarily by the influence of current and local turbulence in the contribution and settlement of premetamorphic larvae (Bustos *et al.*, 1991) High levels of wave exposure also restrict and minimise the presence of mobile predators, increasing survival of settled and early juveniles (Menge and Sutherland, 1976; 1987), and this also includes human intervention by artisanal fishing. In addition, both current and turbulence enhance the level of drifting algae, on which juvenile and adults feed (Bustos *et al.*, 1991) and also maintain the area free of excessive sediments, detritus and faeces that could generate a localised anoxic environment. Turbulent water is also a highly oxygenated habitat.

In this study, coastline exposure was used as an important criterion. It was not possible to measure it, as there was no relevant oceanographic data, such as wave and/or wind intensity and direction available. Consequently, it was necessary to define an indirect, but realistic, way to identify levels of exposure within the study area.

To achieve this, two specific population attributes were selected, scored and combined using the MCE module, in order to extrapolate and produce an output measure of coastline exposure. This estimation was based on the assumption that under normal conditions major substocks of sea urchins are located in highly exposed areas. This is supported by the species preferences and natural behaviour, but also by the fact that major banks correspond to those that remain protected from artisanal fishing as they are situated at highly exposed breaking rocky points and reefs. These are the least accessible sites for extractive diving, at which artisanal fishing is limited to a very small number of sessions during the year (Association of Independent Artisanal Fishermen of Quintay, pers. comm.). Consequently, these are certainly the most attractive fishing locations, as they are rich, and relatively intact.

Using this assumption, mean density and effective coverage (estimated patch size) of major patches in the study area were used to describe the relative magnitude and richness, of each substock, and hence the higher the patch density and coverage, the more exposed was the site.

Mean density and effective coverage thematic layers were scored using RECLASS and attribute files for entering threshold values, which were estimated on a mathematical basis (Table 4.10). As a result, two suitability maps were generated (Fig. 4.18 and 4.19), which were next combined using the MCE showed on Fig. 4.20. The output from MCE was the final suitability map showing different estimated levels of coastline exposure in the study area (Fig. 4.21).

Table 4.10: Threshold values used for used for estimation of coastline exposure.

Score	Criteria	Mean density (individuals/m^2)	Effective coverage (m^2)
1		0-4.7	0-350
2		4.7-11	350-700
3		11-16.5	700-1,050
4		16.5-22	1,050-1,400
5		22-27.5	1,400-1,750
6		27.5-32	1,750-2,100
7		32-38.5	2,100-2,450
8		38.5-44	2,450-2,800
9		44-49.5	2,800-3,150
10		49.5- >55	3,150- >3,500

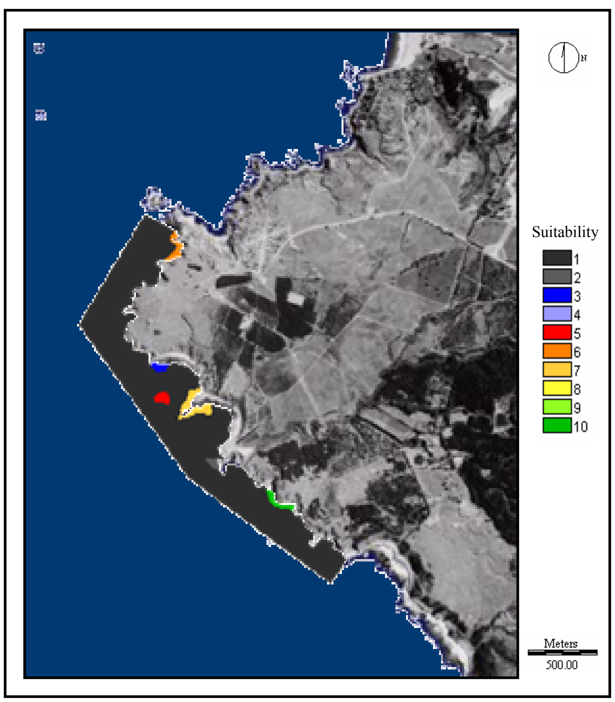


Figure 4.18: Suitability map based on mean density of red sea urchin substocks as a measure of coastline exposure.

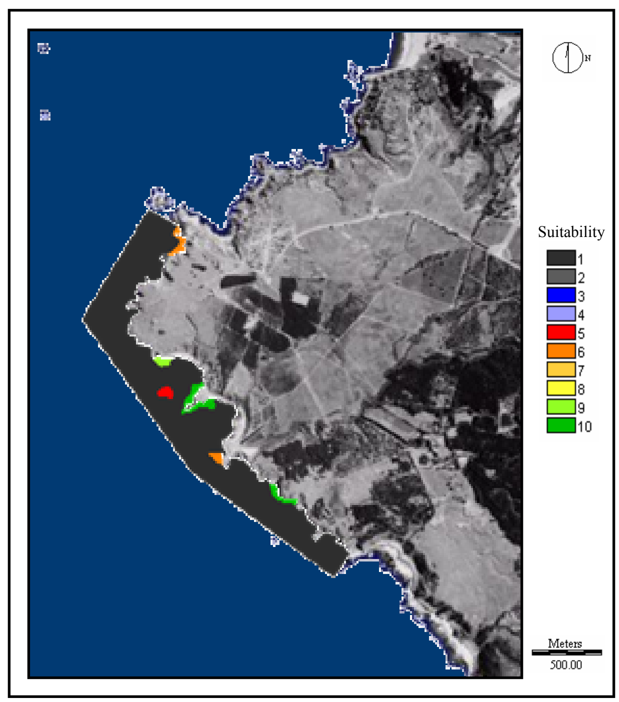
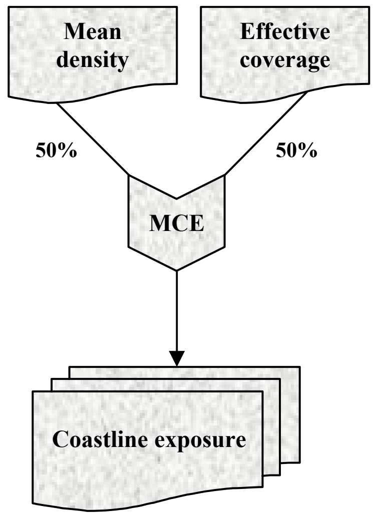


Figure 4.19: Suitability map based on effective coverage of red sea urchin substocks as a measure of coastline exposure.



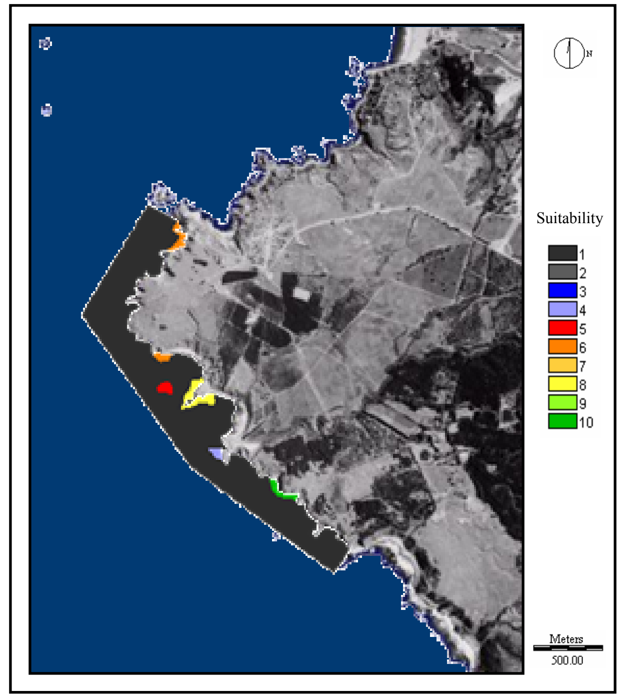


Figure 4.20: MCE used to estimate coastal exposure of the study area.

Figure 4.21: Suitability map based on estimated coastline exposure.

Red sea urchin natural stocks distribution

Studies on sea urchins have reported important positive relationships between recruitment and survivorship of juveniles and adult densities, showing that recruitment development appear to be better around or under adults (Fig. 4.22) (Moore *et al.*, 1963; Ebert , 1968; Tenger and Dayton, 1977; Schroeter, 1978; Sloan, 1980).

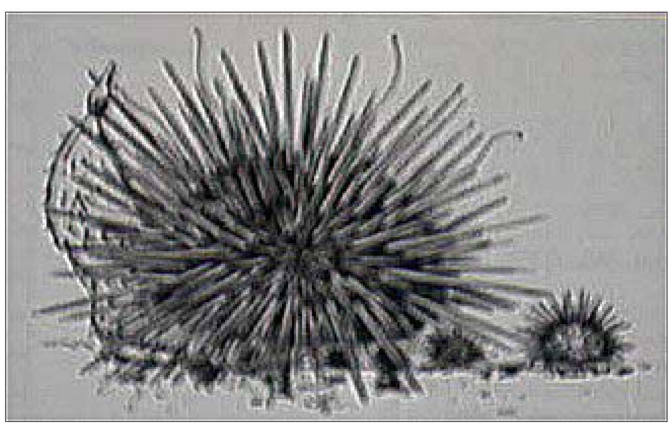


Figure 4.22: Juvenile red sea urchins shelter under the spine canopies of conspecific adults (extracted from Tenger and Dayton (1977))

Breen *et al*. (1985) have shown experimentally that the spine canopy association is a result of juvenile behaviour, where juveniles choose shelter under adults over other protective locations. This association appears to be critical to recruitment success of this species. The spine canopy association provides juveniles with protection from predators (Tenger and Levin, 1983) and the young feed on drift algae snared by adults (Tenger and Dayton, 1977; Breed *et al.*, 1985). Thus depending on the bottom topography, juveniles eventually become too large and must move away from adults (Tenger, 1989).

Stotz *et al.* (1992) studied the effect of the black sea urchin *Tetrapigus niger* on restocked *L. albus* red sea urchin juveniles experimentally, and showed that the presence of black sea urchin adults seemed to favour the survival, but did not affect growth of the seeded individuals. These results correlated well with those previously reported for other species, with regards to the positive relationship between early juveniles and adults and the spine canopy association. In the case of *L. albus*, predation by the sea star *Meyenaster gelatinosus* (Vasquez *et al.*, 1981) and the finfish *Pimelometopon maculatus*, *P. darwini* and *Grauss nigra* (Deppe and Viviani, 1977; Fuentes, 1981) and the otter *Lutra felina* (Seifeld, 1990), are the major causes of mortality (Stotz, unpublished data). Therefore, is possible that shelter from predation is the key factor that would determine the relation between young and adult individuals (Stotz *et al.*, 1992).

Conspecific positive associations between juvenile and adult sea urchins have also been observed for *L. albus* in the experimental restocking programmes developed at Quintay bay (Figueroa and Perez, pers. comm.).

It would also appear that any restocking programme will probably have greater success if based upon sites where major groups of wild individuals exist naturally. At these sites, the species-specific requirements are met, and as a result recruitment, settlement, growth and further individual development takes place effectively.

The distribution of all existing natural substocks of sea urchins was therefore assessed as a key biological criterion for selection of restocking sites. Thus, natural stocks were scored based on the preliminary selection of major substocks carried out during the pilot sampling (Table 4.11). Based on this, only 6 out of 9 identified substocks were selected as major substocks, reflecting the most suitable sites. Although substocks 6, 8 and 9 were not sampled, they were important as a measure of natural distribution, representing suitable restocking sites within the study area (Fig. 4.23).

Table 4.11: Threshold used for red sea urchin natural stocks distribution.

Score	Criteria	Natural stocks distribution
1		-
2		-
3		-
4		-
5		-
6		-
7		-
8		-
9		Substocks 6, 8 & 9
10		Substocks 1 to 5, & substock 7

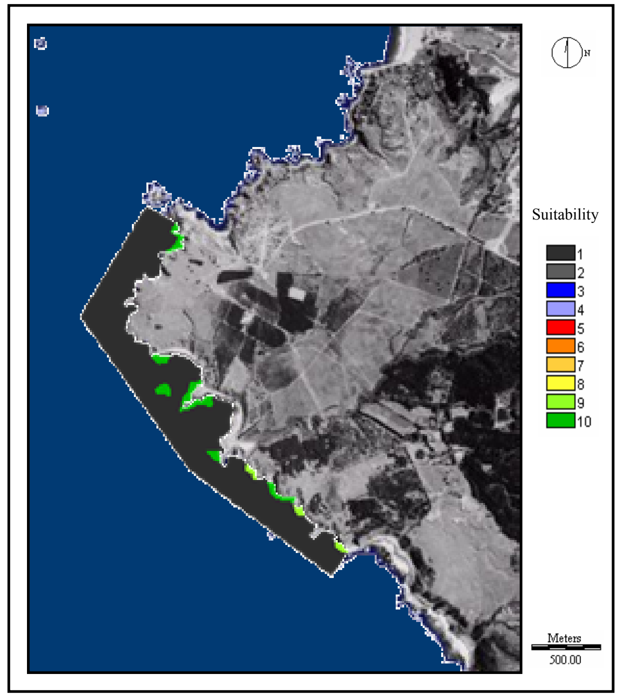


Figure 4.23: Suitability map based on distribution of natural stocks of red sea urchin.

4.4.3 OPERATIONAL FACTORS SUBMODEL

***Bathymetry*[2]**

When performing a restocking exercise for sea urchins, a number of procedures depend upon diving and shore-based operations. Practical implementation and the success of these operations is influenced by water depth. Juvenile urchins are first seeded into shallow and exposed intertidal pools, from where they disperse and this is not constraining, as diving is not essential. However, technicians may have to deal with the practicalities of a highly exposed and abrupt coastline, along with the manipulation of very small individuals, making operations slow and difficult. Following this, implementation of management measures and monitoring, such as prospective surveys or sampling procedures, and reallocation of individuals into subtidal zones, do require diving on a daily basis. Here, the diving technique and so the difficulty and duration of the operation will depend on the bathymetry of the given intertidal or subtidal zone. For example: during a restocking experiment in California divers moved 30,000 small urchins in three days, each diver harvesting and reallocating up to 3,000 juveniles in a day. Here, divers released the young urchins on reefs 10 to 20 m deep (SUHAC, 1997b), which was clearly more difficult than working on a shallow reef ground (3 to 10 m).

Water depth will therefore determine the type and complexity of operations for seeding and management of restocked individuals, and will influence the practical efficiency of any restocking programme.

The bathymetry of the study area was scored (Table 4.12) using information provided by local divers forming the technical unit in charge of sampling procedures and restocking operations at Quintay Bay (Figueroa, pers. comm.). Shallow-based operations (up to 2.5 m depth) could be performed manually. Diving is required from 5 m depth, but can be based on snorkelling. From 10 m onwards diving can only be effectively performed using air compressors, which becomes progressively more difficult as water depth increases and is significantly constraining beyond 30 m. Fig. 4.24 shows the suitability map for bathymetry, based upon the effect on diving operations when performing a restocking exercise of sea urchins.

Table 4.12: Depth threshold values used for bathymetry when influencing restocking operations.

Score	Criteria	Bathymetry (m)
1		45- >51
2		40-45
3		35-40
4		30-35
5		25-30
6		20-25
7		15-20
8		10-15
9		5-10
10		1-5

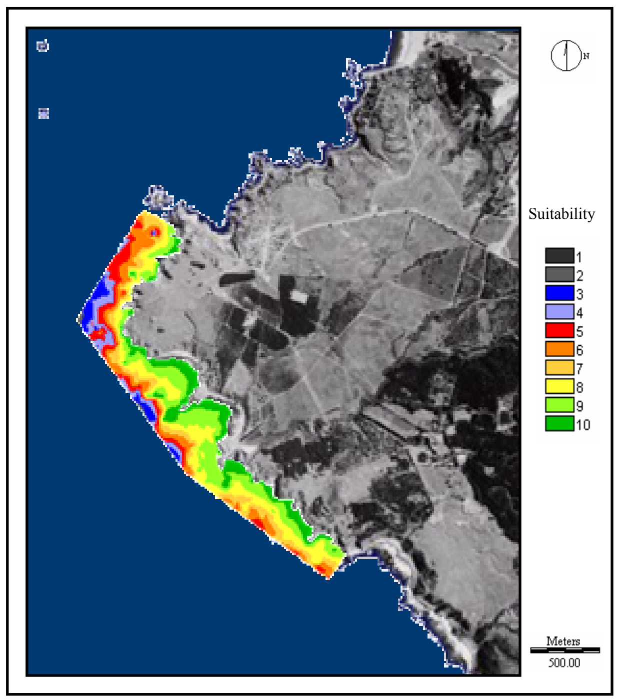


Figure 4.24: Suitability map for bathymetry when influencing restocking operations.

Coastline exposure[2]

As with water depth, the relative exposure of the coastline will constrain a number of operations when restocking. This is particularly relevant in the case of the red sea urchin, as it requires work at highly exposed shores. Here, operations such as diving, sampling, harvesting, and reallocating, will be determined by oceanographic conditions and the degree of wave exposure.

Using the coastline exposure[1] thematic layer generated for the species requirements submodel, coastal exposure[2] was obtained by reclassifying the original categories into their inverse value (Table 4.13). Fig. 4.25 illustrates the final output for coastline exposure as a criterion regulating restocking operations.

Table 4.13: Category threshold values used for coastline exposure when influencing restocking operations.

Score	Criteria	Coastline exposure[1]
1		9-10
2		8-9
3		7-8
4		6-7
5		5-6
6		4-5
7		3-4
8		2-3
9		1-2
10		0-1

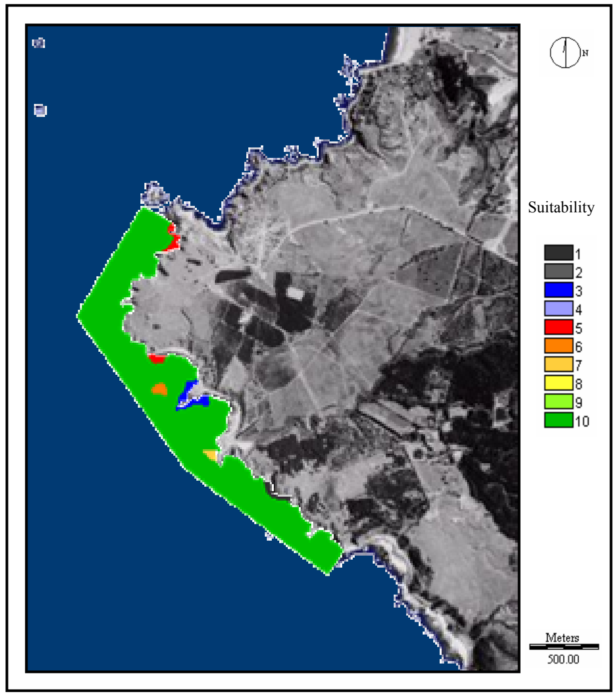


Figure 4.25: Suitability map for coastline exposure when influencing restocking operations.

Accessibility by land

In general, intertidal zones in the Central coast of Chile are not easy to access. Here, the shoreline has an abrupt topography, including cliffs and rocky elevations across the sea-land boundary (Fig. 4.26). Development of access by the shore is nil and only few small walking-tracks are available.

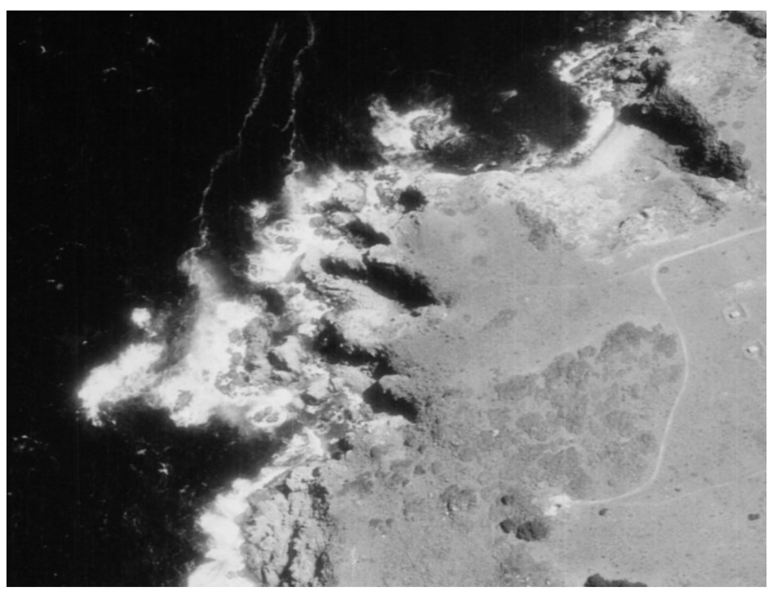


Figure 4.26: Aerial zoom-in of the abrupt shoreline and overland accesses of the study area.

As restocking involves a number of land-based procedures; accessibility to selected seeding sites is a major operational factor. These procedures include transporting of inputs, seeds, various devices and the working team to the site. It is particularity important to move the seed safely and quickly, and ease for a site will be a key factor in successful restocking, further allowing on-site operations such as monitoring, sampling, redistribution, etc.

In the study area, all available access means is by tracks and trails, which have been used by local communities for accessing private properties, lands, and surrounding beaches, and so all operations will be by car and then on foot. These rural roads and tracks were on-screen digitised from a scanned paper map of the study region (Fig. 4.27). Then, using the module DISTANCE, proximity ranges from the various access points to the shore were estimated (Fig. 4.28).

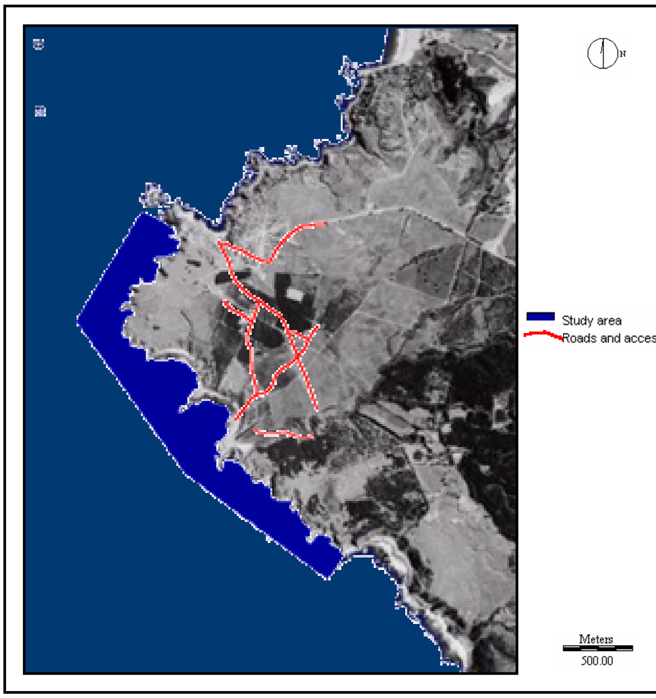


Figure 4.27: Major roads and vehicular access.

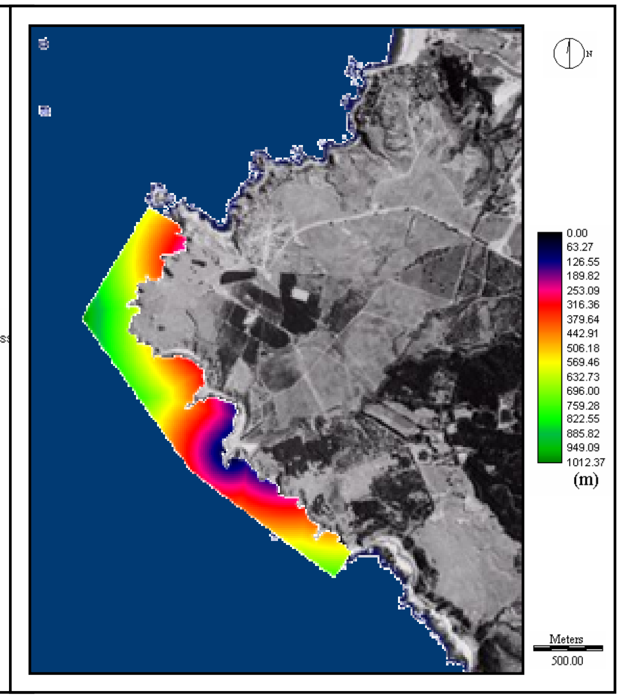


Figure 4.28: Distance to nearest road or access point.

Distance thresholds were then established on a mathematical basis (Table 4.14) and, using value files and RECLASS, distance to roads and accesses was reclassified generating the suitability map for accessibility by land (Fig. 4.29).

Table 4.14: Distance threshold values used for accessibility by land.

Score	Criteria	Distance to roads (m)
1		914- >1,012
2		816-914
3		718-816
4		620-718
5		523-620
6		425-523
7		327-425
8		229-327
9		131-229
10		33-131

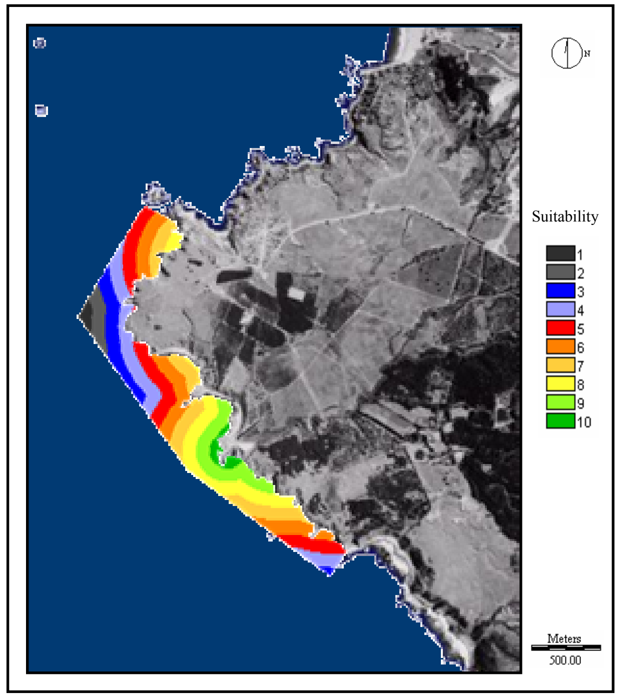


Figure 4.29: Suitability map for accessibility by land.

Accessibility by sea

Site access by sea was also identified as a major factor influencing restocking, as a variety of input working materials, divers and sometimes even juveniles need to be transported to the specific site by sea. A site that is located in close proximity to a boat ramp or beach is preferable, in order to facilitate site access and transportation (Arnold *et al.*, 2000).

This will depend upon the monetary and non-monetary costs associated with the operation with respect to relative site accessibility. Monetary costs relate to costs of transfer from the origin to the restocking site, such as gasoline and motor oil. Non-monetary costs are associated with a so- called *friction-factor* (Issard and Liossatos, 1979; Seijo *et al.*, 1994c). Thus, small artisanal fishing boats would face non-monetary costs or unsatisfactory consequences, such as insecurity and uncomfortable conditions on the boat, which would influence distance travelled from the cove. These, along with other socio-cultural and environmental factors would determine important non-monetary costs assigned to accessibility by sea, in terms of distance from the port (Seijo *et al.*, 1997). With exposed shore fisheries the distance friction factor is even more significant.

In addition to this, distance to restocking sites, which will eventually become fishing grounds, will determine subsequent fishing operating costs, when harvesting takes place over the restocked banks.

For this study, accessibility by sea was measured in terms of the distance of every site from the northern point of the study area (Fig 4.30). The distance between this point and the cove's beach was not considered on this estimation, as it is the only route to a port and thus constant factor.

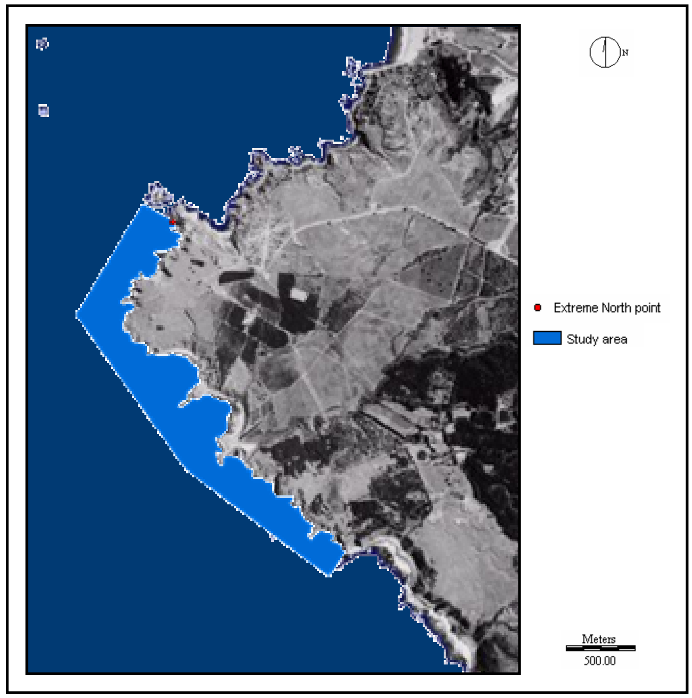


Figure 4.30: Extreme North point of the study area.

Relative distance to the extreme North point (Fig. 4.31) was calculated using the DISTANCE module. Distance threshold values were then estimated mathematically (Table 4.15), and the distance layer was reclassified, using value files and RECLASS module. This generated a suitability map for accessibility to the study area by sea (Fig. 4.32).

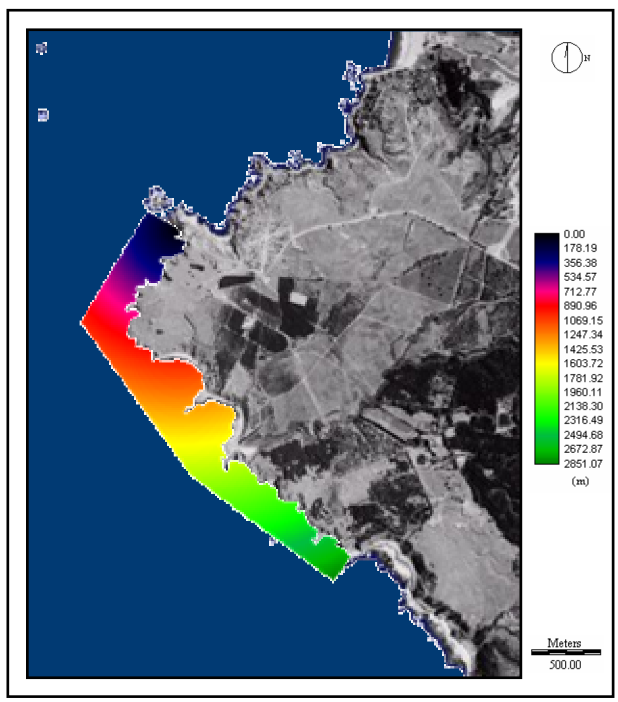


Figure 4.31: Distance to extreme North point.

Table 4.15: Distance threshold values used for accessibility by sea.

Score	Criteria	Distance to N point (m)
1		2,565- >2,850
2		2,280-2,565
3		1,995-2,280
4		1,710-1,995
5		1,425-1,710
6		1,140-1,425
7		855-1,140
8		570-855
9		285-570
10		1-285

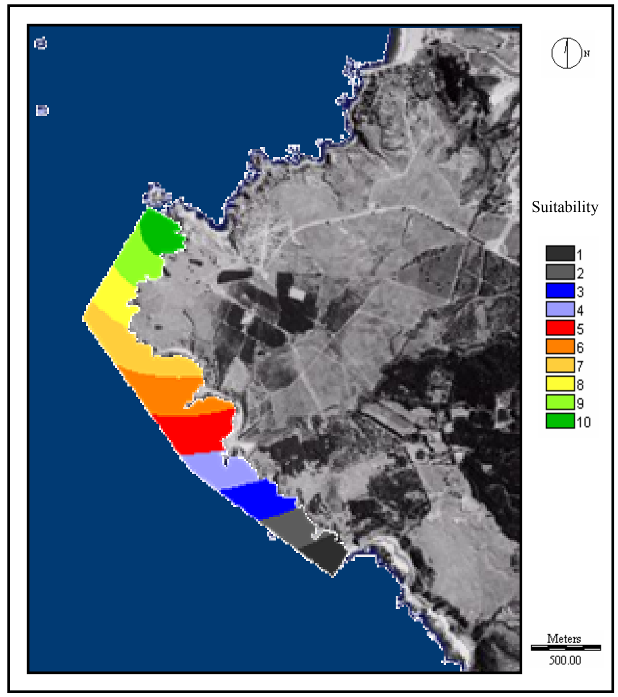


Figure 4.32: Suitability map for accessibility by sea.

4.4.4 AREA AVAILABILITY SUBMODEL

Available area inside red sea urchin natural stocks

Despite the positive association between adult and juvenile sea urchins, and the potentially high suitability of these sites, the available area surrounding them is limited. Consequently, it was necessary to obtain an estimate of each site's available area for the introduction of hatchery-reared individuals, based on a quantification of the area occupied by existing natural stocks of red sea urchin.

In order to quantify available area with regards to the sea urchin natural banks, a percentage calculation was used between the effective coverage of major substocks and the potential inhabitable area surrounding them (Fig. 4.33). For this, thematic layers of effective coverage and potential area were combined, using a mathematical division with the OVERLAY module.

Then, using the percentage correspondence to the scoring system designed, threshold values were defined (Table 4.16) and the final availability map for natural stocks of sea urchin was obtained by simple reclassification, using a value file and RECLASS (Fig. 4.34).

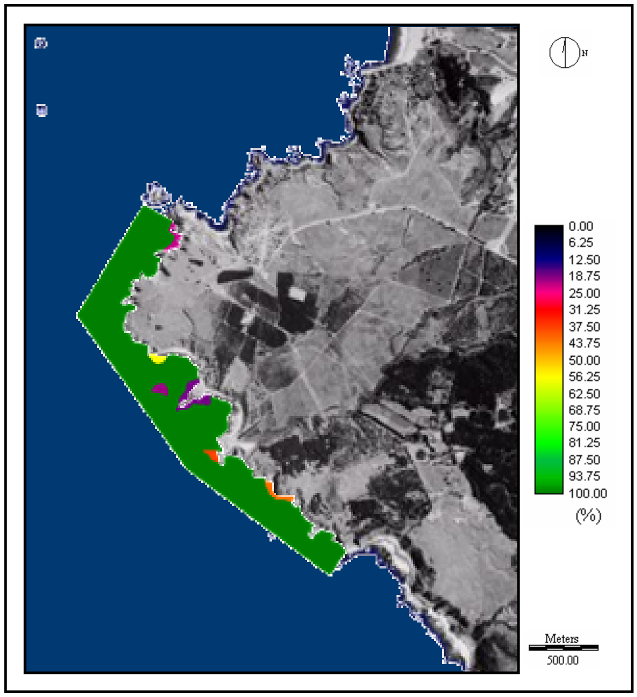


Figure 4.33: Available area (%)within natural stocks of red sea urchin.

Table 4.16: Threshold area availability values[1] used for the two combined criteria.

Score Criteria	Available area (%)
1	-
2	-
3	-
4	-
5	Substock 2 (44.90 %)
6	Substock 7 (58.18 %)
7	Substock 5 (61.95 %)
8	Substock 1 (78.31 %)
	Substock 3 (79.97 %)
9	Substock 4 (81.93 %)
10	Rest of the study area (100%)

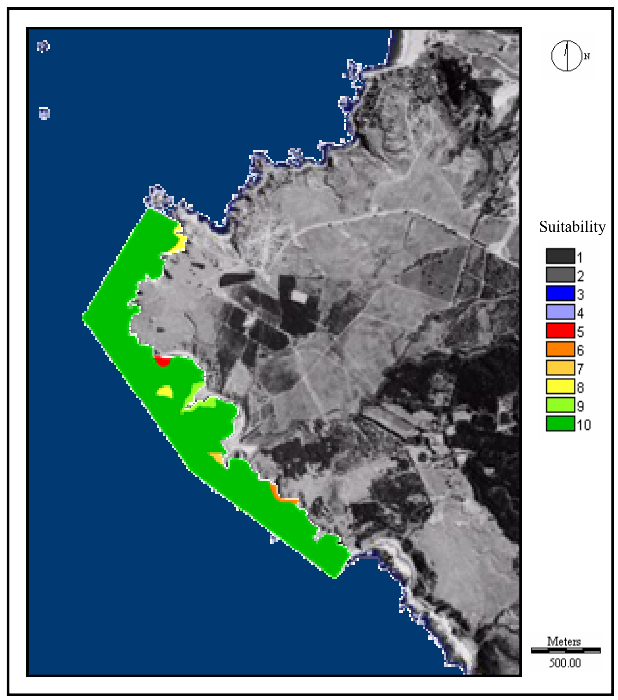


Figure 4.34: Area availability map based on red sea urchin natural stocks.

Available area inside keyhole limpets natural stocks

Although of less commercial interest than "loco"-abalone and sea urchins, keyhole limpets still remain an important source income for local fishermen. At Quintay bay three species of *Fissurella* spp. are exploited on a commercial scale, providing with a income similar to that historically generated by the red sea urchin fishery and half that for "loco"-abalone (del Campo and Perez, 1999).

It was important therefore to determine to what extent, specific zones potentially or currently inhabited by keyhole limpets could eventually be used for restocking sea urchins, so as to avoid conflict with the local fishery for naturally occurring keyhole limpet stocks. To achieve this, it was necessary to model potential inhabitable areas of keyhole limpets, and to compare this with existing distribution patterns within the study area. Then, having identified the areas showing real versus potential keyhole limpet's distribution, logical criterion could be applied to define area availability for potential restocking within these sites.

Inhabitable area suitability for keyhole limpets was defined by a combination between optimal bathymetry and substrate based on the species' requirements. Suitability maps based on both criteria were created by simple reclassification of bathymetric and seabed thematic maps of the study area derived from the thresholds used in the Base Line Study (del Campo *et al*., 1999) for determination of the potential inhabitable area of this species (Fig. 4.35 and 4.36). Then, using the MCE described in Fig. 4.37, these suitability maps were combined to produce the final output, showing inhabitable area suitability for this species within the study area (Fig. 4.38).

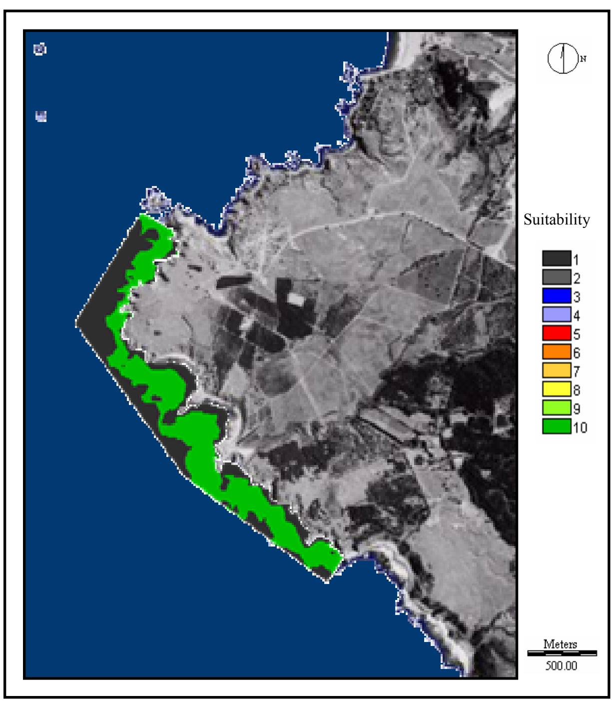


Figure 4.35: Optimum bathymetry for keyhole limpets.

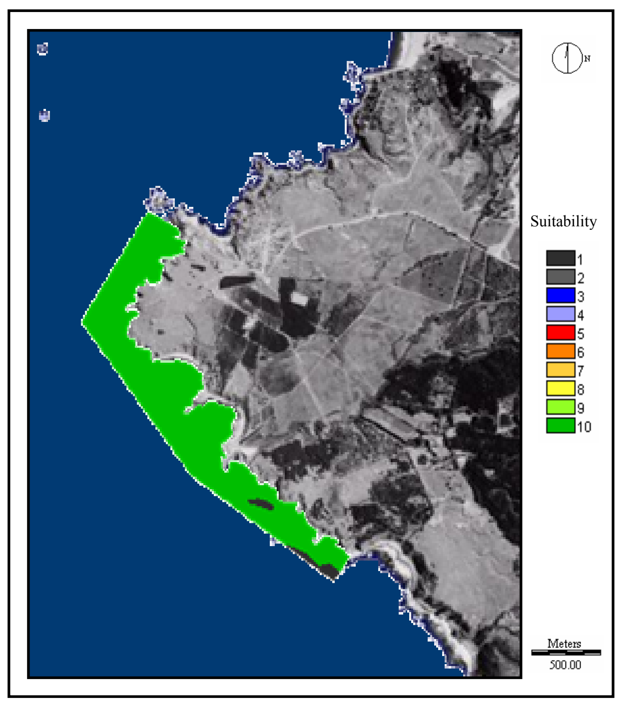


Figure 4.36: Optimum substrate for keyhole limpets.

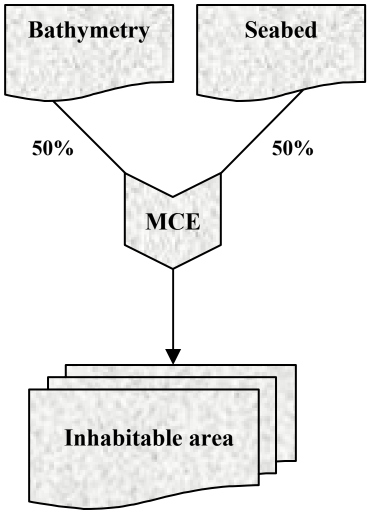


Figure 4.37: MCE used to estimate inhabitable areas for keyhole limpets

Figure 4.38: Inhabitable areas optimised for keyhole limpets.

Having defined the potentially optimal inhabitable areas, these were compared with those areas currently inhabited using the CROSSTAB module (Fig. 4.39).

Thresholds were set established a conceptual basis as described on Table 4.17. Fig. 4.40 shows the final output, describing area availability for restocking sea urchins with respect to natural stock coverage of keyhole limpets.

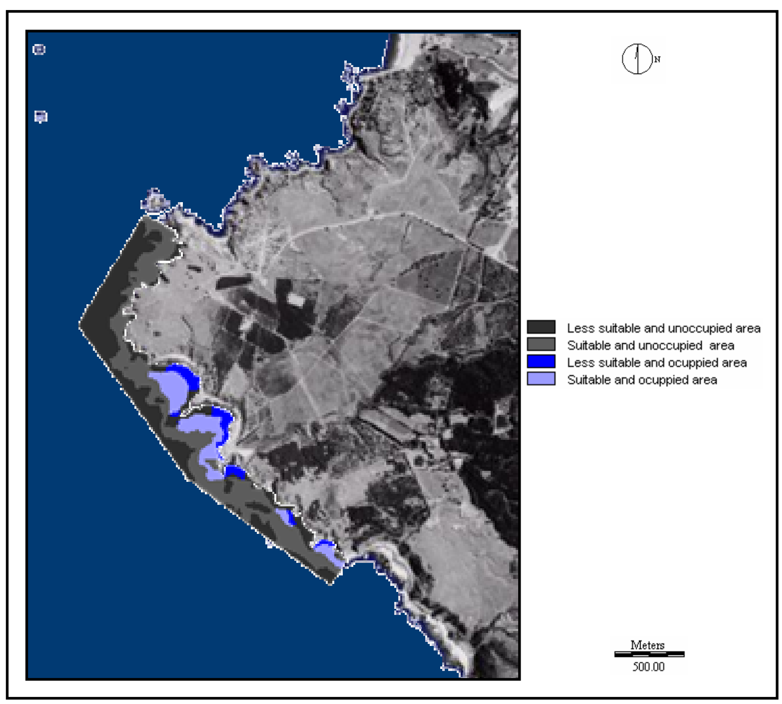


Figure 4.39: Inhabitable area suitability and effective coverage cross-tab map for keyhole limpets.

Table 4.17: Threshold area availability values[3] used for the two combined criteria.

Score Criteria	Area suitability v/s effective coverage
1	Suitable and ocuppied
2	-
3	-
4	-
5	-
6	-
7	-
8	-
9	Less suitable and unoccupied
10	Less suitable and occupied+ Suitable and unoccupied+ Rest of the study area

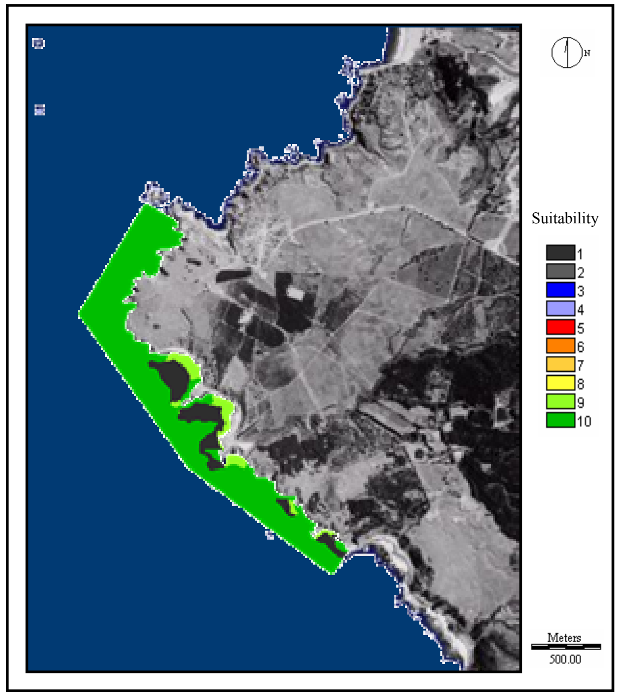


Figure 4.40: Area availability map based on keyhole limpets natural stocks.

Available area inside "loco"-abalone natural stocks

Because of the high value, economic importance, state of overexploitation, and fishing preferences of major natural banks of this resource these were entirely excluded as potential restocking sites for sea urchins. The specific areas occupied by these stocks were scored as totally unsuitable for any sort of alternative management (Table 4.18). The availability map for existing natural stocks of loco-abalone was then generated by simple reclassification of its geographic distribution layer (Fig. 4.41).

Table 4.18: Threshold area availability values[2] used for "loco"-abalone.

Score	Criteria	Area availability
1		All substocks
2		-
3		-
4		-
5		-
6		-
7		-
8		-
9		-
10		Rest of study area

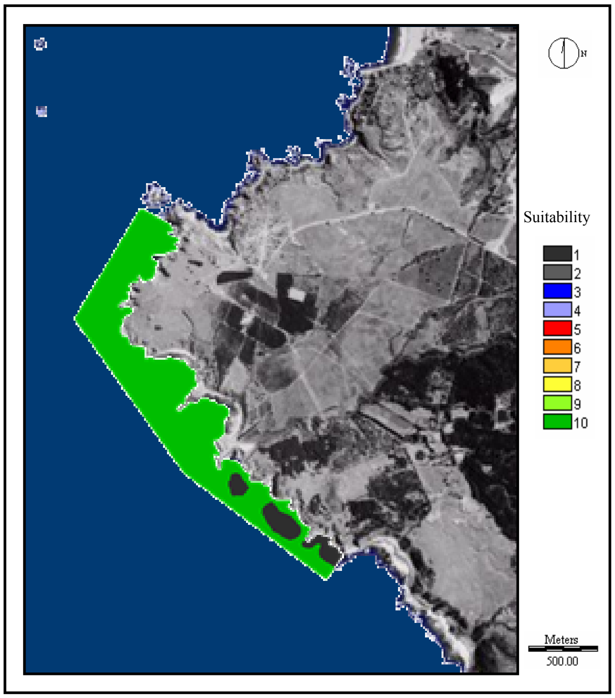


Figure 4.41 Area availability map based on "loco"-abalone natural stocks.

4.4.5 GIS MODELS

Following the generation of the GIS database and the further manipulations to produce the required thematic layers, this section integrates these layers into submodels in order to provide an overall quantification of potential sites for restocking sea urchins at the AMEBRQ.

Species requirements submodel

The four criteria forming this submodel, bathymetry, seabed, coastline exposure and natural stocks distribution, which had been reclassified in terms of optimum areas for restocking, were combined using MCE as shown in Fig. 4.42. Weights of relative importance were derived from a mixed strategy,

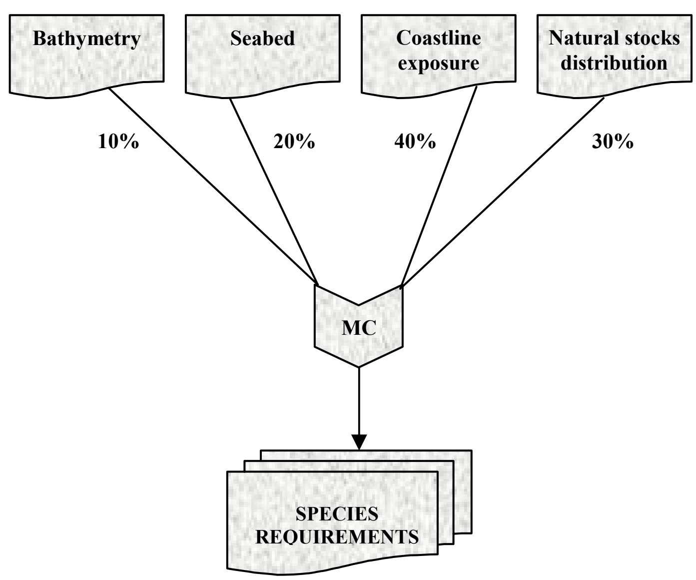


Figure 4.42: Species requirements MCE showing criteria used and estimated weights

using information obtained from questionnaires and personal interviews. Fig. 4.43 shows the resulting suitability map for the species requirement submodel.

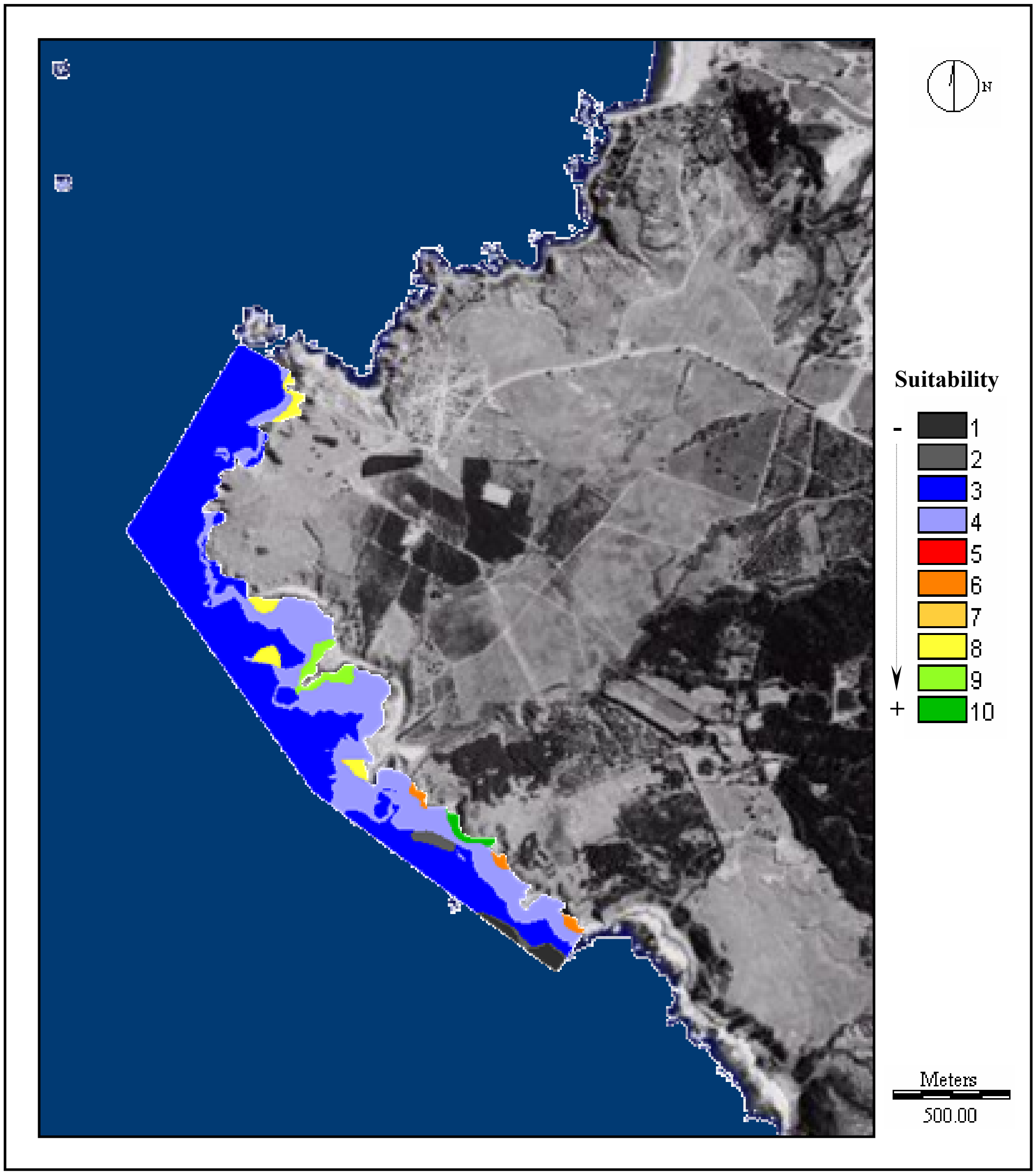


Figure 4.43: Suitability of the AMEBRQ based on specific requirements of the red sea urchin.

Operational factors submodel

The four criteria integrated in this submodel, bathymetry, coastline exposure, by-land and by-sea accessibility, were combined using the MCE shown in Fig. 4.44. For this submodel, weights of importance were estimated from information gathered from questionnaires and personal interviews. Experts consulted were professional divers, and marine biologists forming the technical unit undertaking several experimental and commercial-level restocking exercises carried out at the Quintay Bay. Fig. 4.45 shows the suitability map derived from the operational factors submodel.

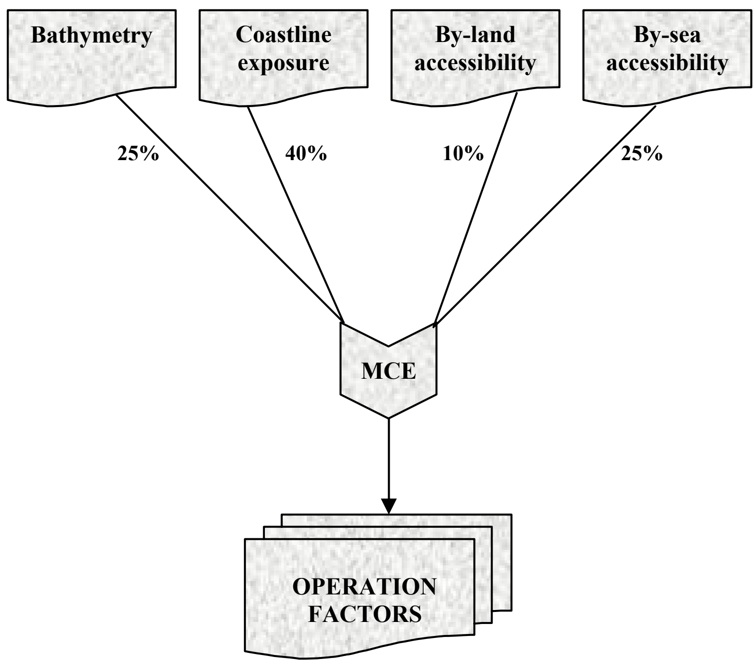


Figure 4.44: Operational factors MCE showing criteria used and estimated weights

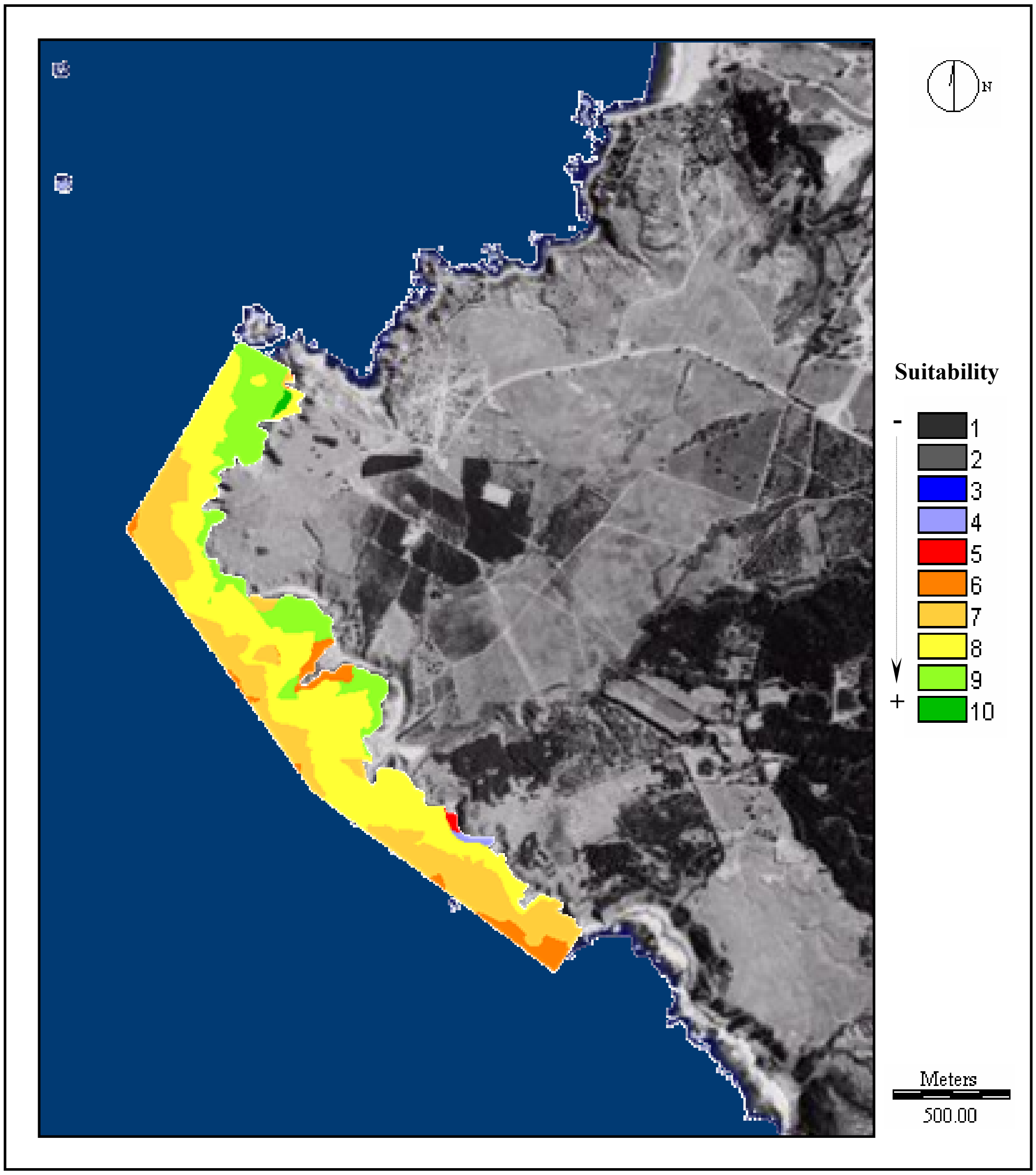


Figure 4.45: Suitability of the AMEBRQ based on the operational factors influencing restocking.

Area availability submodel

The three criteria forming this submodel; the areas occupied by natural stocks of sea urchin, "loco"-abalone and key-hole limpet resources, were combined using a minimum type OVERLAY classification, as shown on Fig. 4.46. This operation allows the production of output pixels representing the minimum of those in the corresponding positions on the first and second image. This enables visualisation of all of the resources area availability in one final image. Fig. 4.47 shows the final availability map representing the effective available area for restocking sea urchins.

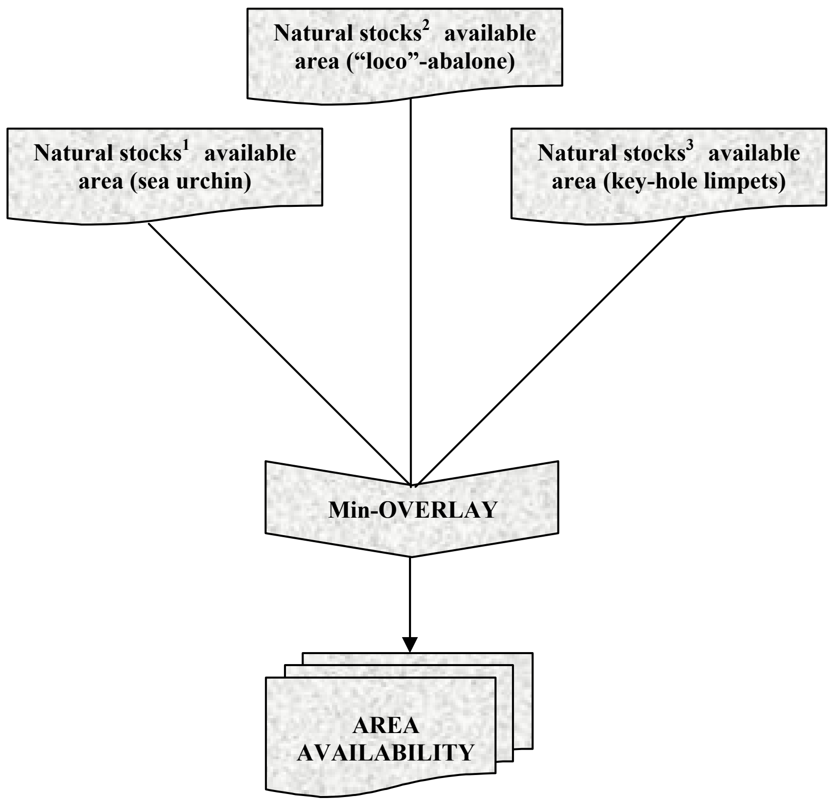


Figure 4.46: Area availability OVERLAY showing criteria used.

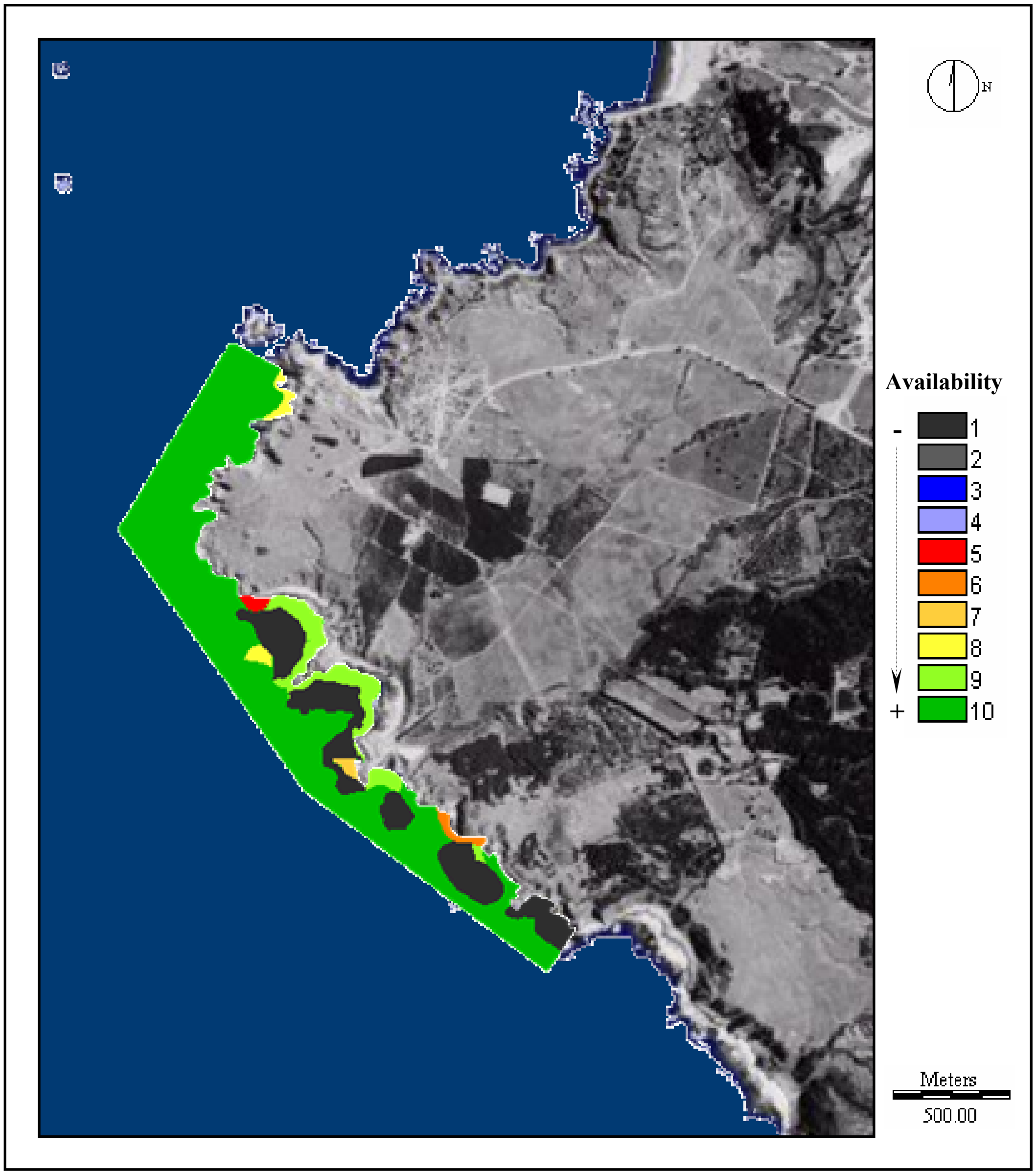


Figure 4.47: Area availability for restocking red sea urchins based on the current occurrence of benthic resources in the AMEBRQ.

4.4.6 FINAL OUTPUT AND SITE SELECTION

Using the outputs from the submodels on species-specific requirements, the operational factors and the final area availability map, the last stage was to integrate these layers into the final output, so as to identify and quantify the optimum areas for restocking.

For this, the two suitability maps (Fig. 4.43. and 4.45) were first combined using the MCE (Fig. 4.48), to produce a suitability layer based on species-specific requirements and operational factors (Fig. 4.49). This was then combined with the final availability map using a CROSSTAB-classification. This procedure allowed identification of all possible combinations between suitability and availability. Fig. 4.50 shows the final CROSSTAB-classified suitability ¦ availability map for restocking sea urchins in the AMEBRQ.

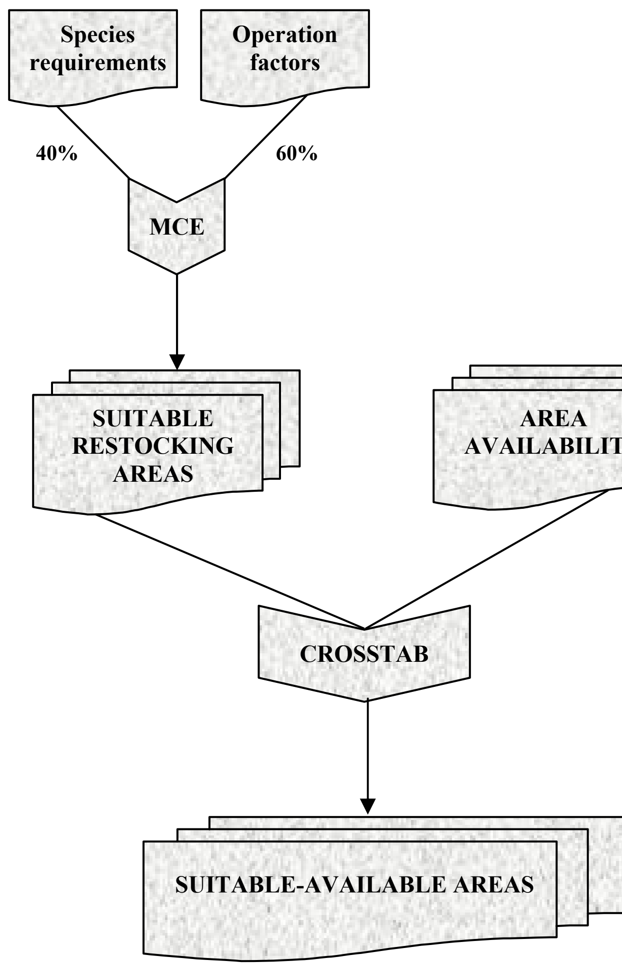


Figure 4.48: Final model integration showing MCE and CROSSTAB combinations used.

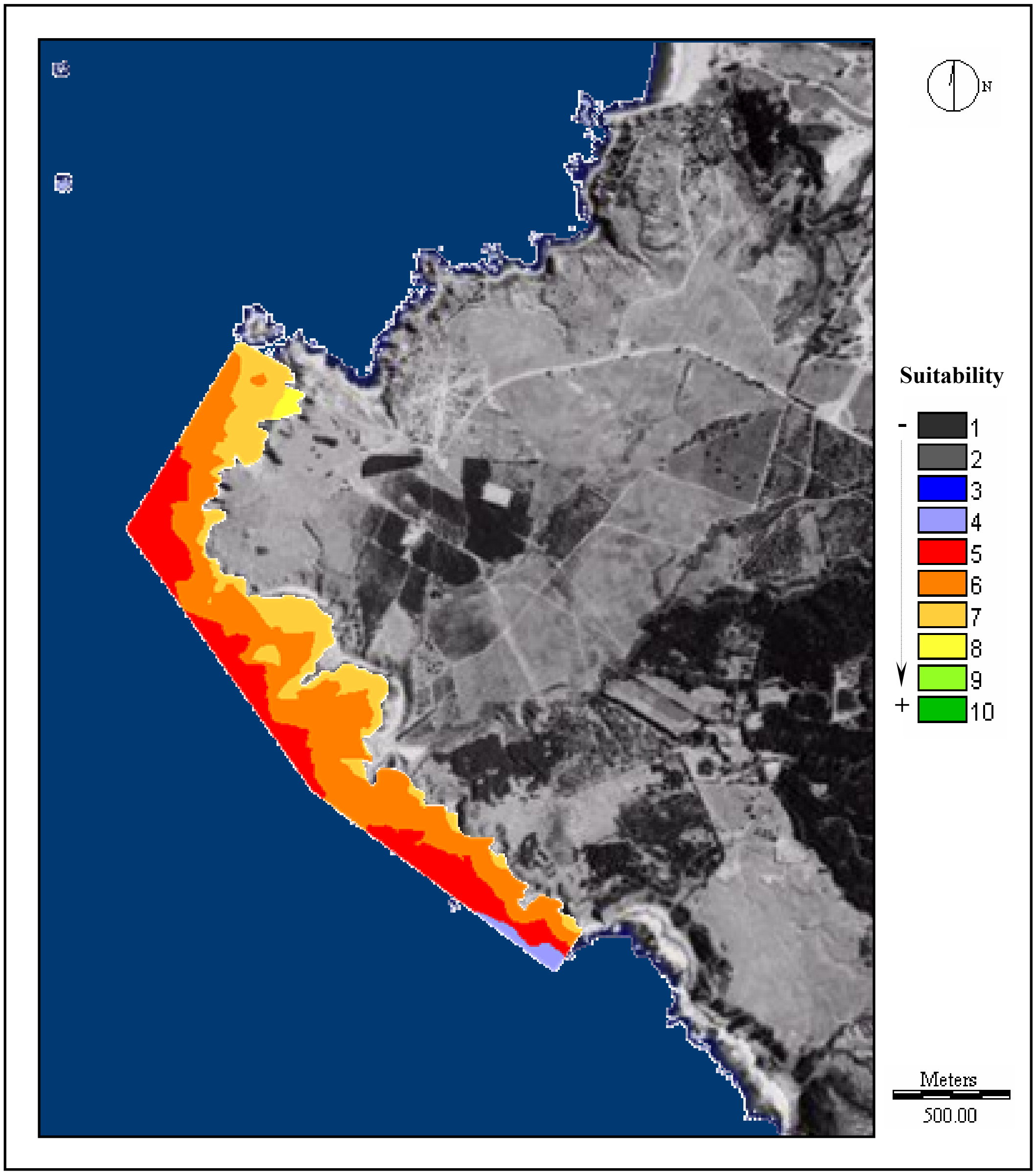


Figure 4.49: Overall suitability map for sea urchin restocking based on the specific requirements of the species and operational factors.

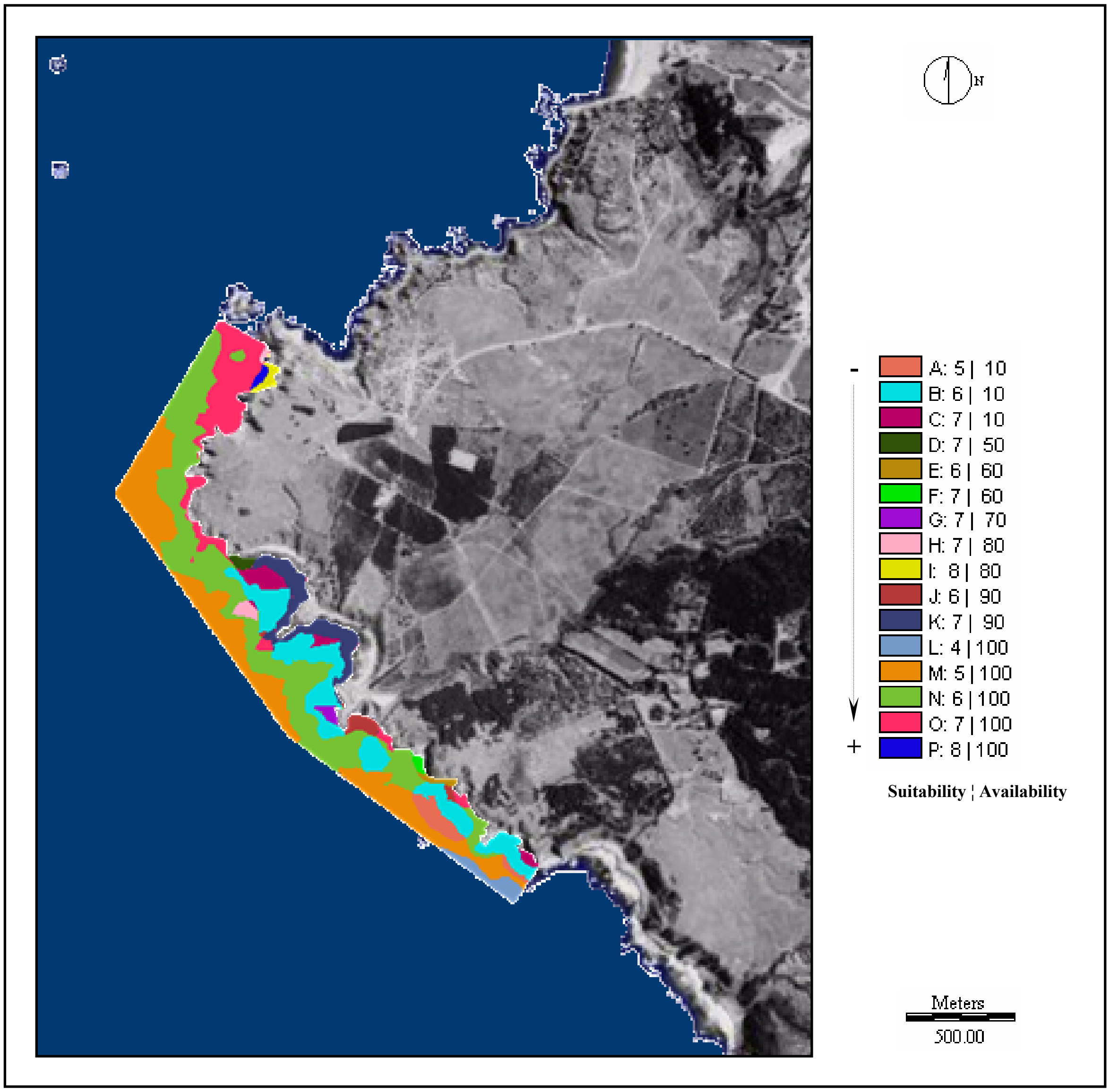


Figure 4.50: Final CROSSTAB- classification suitability ¦ availability map for red sea urchin restocking site selection in Quintay, Chile.

Taking into account the effective area availability, the area for each suitability ¦ availability site combination (site categories) was estimated, and the overall area for each site category was calculated (Table 4.19). For this, all categories resulting from the CROSSTAB-classified suitability ¦ availability map were first grouped using the GROUP module. Then, the area of previously grouped categories was calculated using the AREA module. Finally, the resulting layer (m^2) was overlaid with the final available area layer (%) using the product-OVERLAY module.

The following table includes all the individual sites forming each category, including its area in square meters, and the overall sum in square meters and hectares, and percent proportion of the total AMEBRQ area that this represents.

Table 4.19: Specific and overall area estimation for each suitability ¦ availability site category.

Category	Suitability ¦ Availability	Site 1	Site 2	Site 3	Site 4	Site 5	Total area (m^2)	Total area (Ha)	%
A	5 ¦ 10	2,181	395				2,576	0.26	0.31
B	6 ¦ 10	2,295	2,485	1,774	6,194	3,263	16,011	1.60	1.94
C	7 ¦ 10	1,634	437	407			2,478	0.25	0.30
D	7 ¦ 50	2,809					2,809	0.28	0.34
E	6 ¦ 60	2,918					2,918	0.29	0.35
F	7 ¦ 60	2,104					2,104	0.21	0.26
G	7 ¦ 70	3,758					3,758	0.38	0.46
H	7 ¦ 80	1,380	5,288				6,668	0.67	0.81
I	8 ¦ 80	5,331					5,331	0.53	0.65
J	6 ¦ 90	609	9,219	2,329			12,157	1.22	1.47
K	7 ¦ 90	56,167					56,167	5.62	6.81
L	4 ¦ 100	19,367					19,367	1.94	2.35
M	5 ¦ 100	90,629	82,909	74,032			247,570	24.76	30.02
N	6 ¦ 100	310,975	12,136				323,111	32.31	39.18
O	7 ¦ 100	89,466	18,165	3,656	3,340	3,037	117,664	11.77	14.27
P	8 ¦ 100	3,921					3,921	0.39	0.48
Mean	**6.44 ¦ 69.37**					**Total**	**824,610**	**82.46**	**100**

After each site category was identified, and its effective available area was estimated, the last stage was to define a logical standard for final site selection decision-making. For this, site categories were selected by establishment of an order of priorities, where the best option was the higher suitability ¦ availability combination, and the worst the lower combination.

Based on this, threshold values for site categories were set (Table 4.20), and the data in Fig. 4.50 was reclassified. Fig. 4.51 shows the final map for sea urchin restocking site selection. Here, scores represent an integrated suitability index (suitability and availability), and orders of priority are options (sites) to be selected for a restocking exercise in the study area. Finally, Table 4.21 lists and describes the 5 highest priority options, which includes the 10 best sites selected and proposed for restocking sea urchins in Quintay, Chile.

Table 4.20: Site category thresholds used for final site selection.

Score Criteria	Site category	CROSSTAB-classification suitability ¦ availability
1 10 th option (worst)	A; B; E; J; L; M; N	6 ¦ 100; 5 ¦ 100; 4 ¦ 100; 6 ¦ 90; 6 ¦ 60; 6 ¦ 10; 5 ¦ 10
2 9 th option	C	7 ¦ 10
3 8 th option	D	7 ¦ 50
4 7 th option	F	7 ¦ 60
5 6 th option	G	7 ¦ 70
6 5 th option	H	7 ¦ 80
7 4 th option	K	7 ¦ 90
8 3 rd option	O	7 ¦ 100
9 2 nd option	I	8 ¦ 80
10 1 st option (best)	P	8 ¦ 100

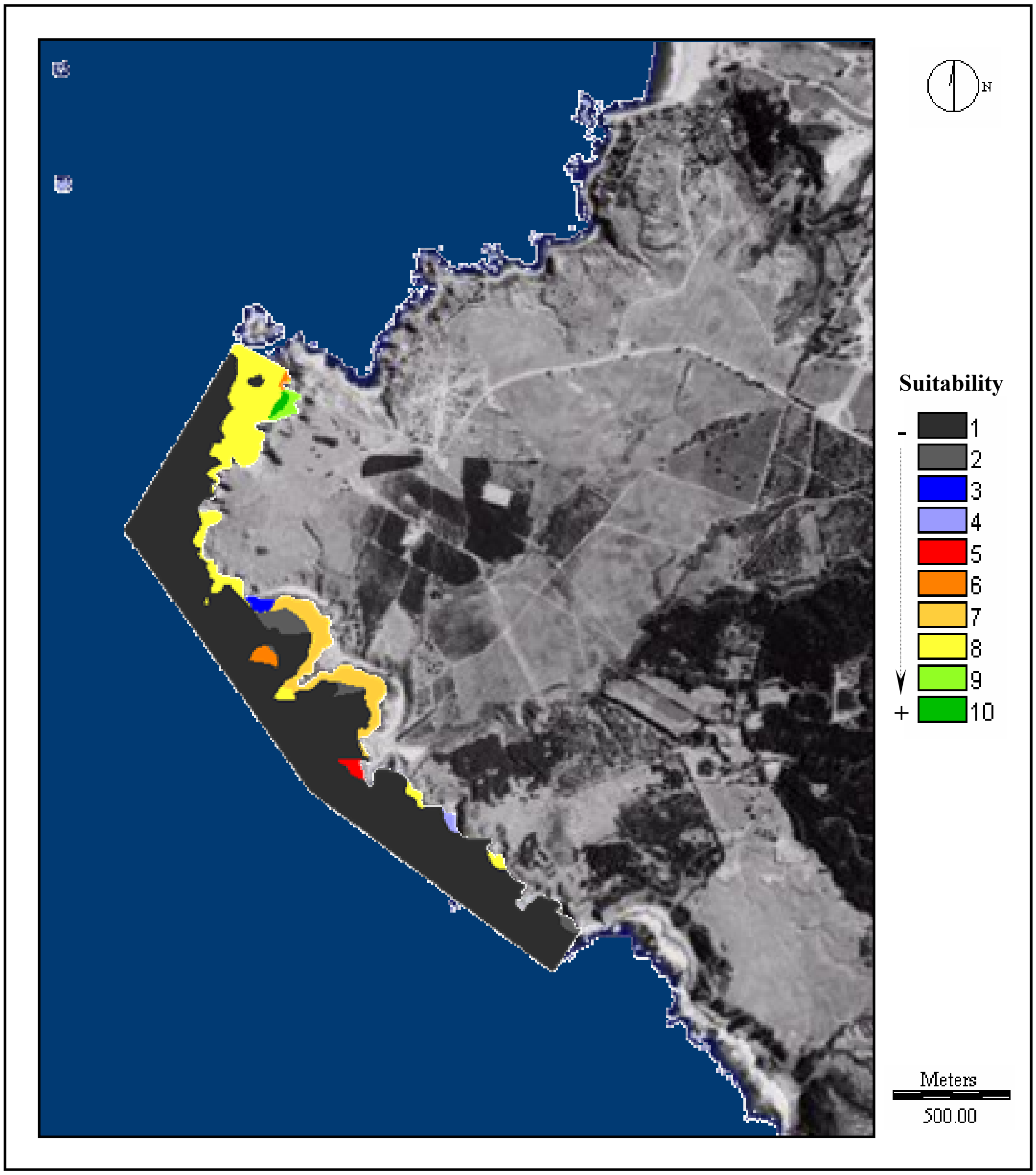


Figure 4.51: Final prioritised sea urchin restocking-sites options at the AMEBRQ.

Table 4.21: Estimated area of sites selected for a sea urchin restocking exercise in the area of management and exploitation of benthic resources of Quintay (AMEBRQ), Chile.

Priority	Integrated suitability index	Area (m^2) Site 1	Site 2	Site 3	Site 4	Site 5	Total (m^2)	Total (Ha)
Best option	10	3,921					3,921	0.39 (2.07%)
2nd best option	9	5,331					5,331	0.53 (2.81%)
3rd best option	8	89,466	18,165	3,656	3,340	3,037	117,664	11.77 (62.01%)
4th best option	7	56,167					56,167	5.62 (29.60%)
5th best option	6	1,380	5,288				6,668	0.67 (3.51%)
Mean	**8**	**-**	**-**	**-**	**-**	**Total**	**189,751**	**18.97 (100%)**

4.5 DISCUSSION

This research was focused on the development of a bioeconomic and spatial model for optimisation and management of the red sea urchin fishery *Loxechinus albus* in Chile. The GIS-based restocking model (GISRM) constituted an essential element, the main objective of which was to support decision-making for the identification, quantification, selection and proposal of suitable sites for restocking this species.

The model objectives were achieved by the selection of determinant criteria influencing restocking activities. These were considered as three GIS-based models (species requirements, operational factors and area availability), which were built based on hierarchical structures. Once models were structured, decision maker's preferences were incorporated by means of scoring and weighting systems. The ultimate aim was then to combine the main elements of multicriteria analysis: criteria (factors) and decision maker's preferences (weights), using decision rules or multi-criteria evaluation (MCE) to produce the final output.

The final output was a CROSSTAB-classification suitability¦availability map showing all possible combinations of suitability and area availability for restocking on all sites within the study area. From this, final site selection for restocking was based on the identification, quantification and selection of higher suitability¦availability combinations (site categories). As a result the five best options, considering ten sites with an overall area of 19 Ha and an 8-point average integrated suitability index, were selected (Fig. 4.51 and Table 4.21).

When modelling site selection for restocking sea urchins, selection of determinant criteria influencing the activity was perhaps one of the most difficult tasks. As reported for other benthic species (Berrigan, 1996), multiple criteria must be also considered when determining the suitability of a site for sea urchin restocking. Even when multiple factors can be identified, available data can be restrictive, so reviewing all of them is often not possible. This limitation is typical for most GIS systems, good and standard quality data being the most important but scarce resource. For this reason, an adaptive and flexible selection approach must be considered when modelling a natural resources-based system, towards balancing the trade-off between the importance of a factor in the system and availability of data for the case study.

Selected criteria in this study were similar to those previously reported in research relevant to site selection for restocking and grow out aquaculture of other benthic species (Krieger and Muslow, 1990; Peterson *et al.*, 1995; Berrigan, 1996; Barbieri and Silva, 1996; Parker *et al.*, 1998; Arnold *et al.*, 2000). Among these, the choice of appropriate bottom habitats (substrate), and sites within natural habitat and distribution of biological resources has been shown to make a large contribution to the success of a seeding program. Suitable sites have also been identified based on local knowledge of sites of known quality, which have historically supported substantial natural production or are characterized by suitable water quality for growth and survival of targeted organism. Factors associated with site access such as proximity to transportation corridors and other human-use facilities have also been recognised as determinant criteria.

With reference to the Chilean red sea urchin, investigations on experimental restocking in the Central-North and South coasts have shown that the major factors influencing site selection are water current and coastline exposure, bathymetry and seabed slope, substrate type, algae coverage, presence of predators and distribution of conspecific wild stocks (Bustos *et al.*, 1990; 1991; Stotz *et al.*, 1992; Barbieri and Silva, 1996; Figueroa, 2000).

With the exception of algal coverage and distribution of predators, the present model addressed most of the factors previously named and also accounted for additional aspects relevant to restocking operations, and area availability for implementing a restocking exercise.

The relative importance of determinant factors is not uniform, and their influence and interaction may vary with time, space and geographic location. However, most authors have found that appropriate combinations of shallow-water pools in exposed rocky bottom intertidal shores with occurrence of natural existing conspecifics, and low densities of predators are the most suitable sites for incorporating sea urchin juveniles.

Even though food resource is certainly important, its local distribution may not be a crucial condition for development, and hence is not a determinant for site selection for this species (Bustos *et al.*, 1991), as *L. albus* mainly feeds-on drift algae (Castilla and Moreno, 1981; Contreras and Castilla, 1987; Moreno and Vega, 1988), and available algae may not entirely depend on local distribution, especially in highly exposed areas.

Characterizing habitat for restocking sea urchins in southern Chile, Bustos *et al.* (1991) found there was no significant statistical relationship between macroalgae presence and sea urchin distribution. The ecological role of this species is not comparable to that described for *Strongylocentrus* spp. in Californian coasts (Lawrence, 1975; Foster and Schiel, 1985); *Paracentrotus lividuc* in the Mediterranean sea (Nedelec, 1982; Velarque and Nedelec 1983) or *Diadema antillarum* in the Indian ocean (Ogden et al., 1973; Sammarco, 1982). On the contrary, due to its unspecific and non-selective feeding habits, *L. albus* neither controls nor regulates macroalgae distribution and abundance in adjacent habitats (Castilla and Moreno, 1981). Studies of natural sea urchin stocks protected from human exploitation over 6 years in southern Chile have demonstrated that, food is not a restrictive factor for the development of the population, whose size may increase independently of local food availability (Lepez, 1988).

However, the presence and distribution of predators, has been reported as the major source of mortality of small individuals (Stotz *et al.*, 1992). However, as most predators are mainly trophic generalists showing active capture behaviours on highly heterogeneous habitat (Morales and Antezana, 1983; Moreno and Vega, 1988; Moreno and Zamorano, 1980), pressure on sea urchins may be alleviated if alternative prey is available (Bustos et al., 1991).

Regardless of this relative advantage for restocking, overall: intrinsic predator mobility, non-specific prey-predator association and heterogeneous habitat make the distribution of predators an extremely difficult variable to assess and refer spatially. For that, the mapping and modelling of geographic distribution of predators remains a major unresolved issue which should be developed in further studies on the coastal management of this species. The definition of quantitative ecological and spatial prey-predator relationships, geographic distribution of main targeted resource and of predators could be used as a further approach.

As for most biotic factors in open-marine environments, both food resource (macroalgae) and predators distribution show high seasonal and spatial variability. This may result in variable habitat classification (Bustos *et al.*, 1991). By contrast, abiotic factors such as bathymetry and seabed type show less or no variability, and for this reason habitat characterization offers best long-term results if they are considered. These factors must be part of the baseline assessment for restocking site selection (Bustos *et al.*, 1991).

Among abiotic factors, intertidal exposure is considered to be perhaps the most determinant criterion influencing natural distribution of sea urchins, and hence site selection for restocking (Bustos *et al.*, 1991; Stotz *et al.*, 1992; Figueroa, pers. comm.). Consequently, coastline exposure was highly weighted in the species requirements submodel, although unfortunately direct measurement of this factor was not carried out. Given its significance, the development of effective methodology should be a priority for future research.

In this context, very little oceanographic data is available for the Chilean coastline. However, some interesting remote sensing (RS) approaches have been used to determine restocking zones for benthic resources through analysis of ERS-1 and SPOT images to discriminate protected or exposed areas in the Valparaiso Region (Barbieri and Silva, 1996). Using time series modelling at higher resolution, this methodology may be effectively used to identify degree of wave-exposure along a given shoreline.

Unlike previous studies on restocking site selection for sea urchins in Chile, this research took into account not only biotic and abiotic requirements of the species, but also operating factors associated with the practical performance of the seedling exercise. Similar considerations have been recently used on lease site selection based on GIS-applications for hard clam grow-out site selection in Maine (Parker *et al.*, 1998) and Florida (Arnold *et al.*, 2000).

In this context, the accessibility of a site measured as a relative distance from or to different input or output points such as ports, boat ramps, cage-systems, services and rough material, markets, processor plants and freezing industry, have been used as key points in relevant studies on aquaculture site selection using GIS-based models (Krieger and Mulsow, 1990; Aguilar-Manjarrez, 1996; Salam, 2000; Perez-Martinez, 2002; Perez-Sanchez, 2002).

The very steep, exposed and mostly inaccessible shoreline of the Chilean coast imposes important constraints to site access by both sea and land. This is more evident in the Central and North coast, where strong swell and winds bathe an open coastline, with very few protected regions. Effective application of a restocking programme, monitoring, manipulation of released stock and later fishing or recapture operations are also strongly determined by the site's accessibility. Operational practicalities rely on both regional proximity to the restocking zone and localized ease of access at the intertidal or subtidal site itself. The first is determined by proximity to inland roads and tracks, but also by relative distance to the ramp or cove's main beach. The second is represented by the site's bathymetry and coastline exposure.

For biological, physical, spatial, and operational reasons, specific location of the grow-out site for sea urchins may largely determine the long-term success of a restocking programme. In this context Berrigan (1996) described the need to identify and select sites that support economically viable growth and survival while not directly or indirectly interfering with local ecosystem functions such as primary production, navigation, alternative uses, and natural fisheries. Navigation or alternative uses are not actual constraints, however as under the Chilean system assigned areas may only be used for management and exploitation of benthic resources, restocking and any management strategy must aim to avoid conflict with naturally occurring conspecific and/or other fisheries.

Bearing this in mind, the present study attempted to provide a method for estimating the effective available area for restocking within the coastal lease concerned. For this the area availability submodel was developed on the basis of geographic distribution, effective coverage, relative commercial impact and specific requirements of major benthic resources targeted at the study area.

In general, most management areas consider the exploitation of more than one species of commercial importance, such as sea urchins, keyhole limpets, "loco"-abalone, macroalgae, etc. Management of these species must therefore consider compatible exploitation plans, prioritising development of high-value species (Stotz *et al.*, 1992). If it is considered that both the red sea urchin and keyhole limpets require "clean" rocky bottoms (without ascidians), then generating this substrate will favour their settling and growth, but also may result in severe exclusion of "loco"-abalone, which mainly feeds on this resource. Because of this, real possibilities for multiple species management and exploitation in a single area are reduced, and must be therefore carefully studied on the basis of the requirements of each species (Stotz *et al.*, 1992). Numerous field-based studies have demonstrated tremendous variability in ecological processes on several spatial scales between replicate sites of what appear to be identical habitat type and conditions (e.g.: Caffey, 1985, Peterson and Beal, 1989). For this, site-specific ecological and environmental information is extremely important for the success of any culture operation (Peterson *et al.*, 1995).

In conjunction with on-site surveys, future research should be focused on the establishment of more explicit policies and limits to regulate restocking activities under the AMERB system in Chile. A good example is the case of the State of Florida where regulations for grow-out aquaculture specifically require that hard clam leases be located in areas containing natural densities of less than five clams per m^2, and in areas that are essentially devoid (1% coverage or less) of rooted aquatic vegetation (Arnold *et al.*, 2000). This was intended to avoid conflict with wild stocks and conservation of natural habitats. Similarly, Rubec et al. (1998) noted the need to amend fisheries management plans so that they include the identification of essential fish habitat (EFH) (Brown, 1998), mandated in the Marguson-Stevens Fishery Conservation and Management Act. EFH was defined as “those waters and substrates necessary for spawning, breeding, or growth to maturity”. Additionally, the administration recognized the need to use GIS to define and manage estuarine and marine habitats spatially (Rubec *et al.*, 1998).

The Chilean fishery system is rather general. This is based on the premise that the management zone must be the natural habitat of the main specie(s) targeted in the management and exploitation plan (MEP). The MEP must consider resource and environmental conservation, and avoid any disturb or impacts on the environment. Furthermore, management cannot consider introductions of individuals from areas other than the AMEBR. Nevertheless, aquaculture produced seed is allowed; and in specific cases, a one-time introduction of outside individuals may also be permitted (SernaPesca, 1996).

After defining the determinant factors, these were divided into three submodels, which were then structured hierarchically into the overall GISRM. Hierarchical structures have been acknowledged as a powerful version of reality when analysing a complex system of interacting components (Saaty, 1977), and this method was found to be very efficient and approachable for modelling multicriteria based-activities.

As reported in recent similar studies (Perez-Martinez, 2002) the scoring system from 1 to 10, as used for this study, is probably the most suitable scale, as it is easy to use and most intuitive. The same scoring system has been presented by Lowry *et al.* (1995) and Abdel-Kader *et al.*, (1998), and a 1 to 100 was used by Krieger and Mulsow (1990). Further to the scoring process itself, the use of questionnaires and personal interviews with experts was essential to provide sets of threshold limits for specific criteria, when no relevant data was available or mathematical estimation was not permissible. The objective of criterion weighting was to express the relative importance or influence of each criterion into the activity. For this, direct estimation of weights in terms of percentages, obtained from different sources of information, was used as the major approach.

From a number of criterion-weighting procedures available in the literature, the pairwise method has been recognized as the most effective technique for spatial decision-making (Eastman, 1993; Malczewki, 1997). This is based on the comparison between pairs of factors, forming a comparison matrix for computation of criterion weights and estimation of a consistency ratio, and this method has been used for most recent aquatic GIS works undertaken (Aguilar-Manjarrez, 1996; Salam, 2000; Perez-Martinez, 2002; Perez-Sanchez, 2002) using a built-in module available in IDRISI32. Important difficulties have been described when using this method as part of the questionnaires for external agents and focus groups. Perez-Martinez (2002), considered that even though the 1 to 9 scale was mostly accepted, many participants suggested that a 1 to 10 scale would be more intuitive, Moreover, some decision-makers agued that it was easier for them to assign the weights directly to factors without going through the tedious process of completing the pairwise matrix. This was the main reason here to define a direct percent weighting system for both the author's and external expertise preferences setting, when questionnaires were used. This technique may be effectively used only if the number of factors is relatively small, i.e.: 2 to 4 factors. If dealing with a greater number of factors (more than 4) on each submodel the pairwise comparison method should be considered, as it provides an index to estimate the overall consistency between the weights defined (consistency ratio (CR)).

Although previous studies on GIS-based models for site selection, have often used questionnaires to allow different users to weight criteria (Aguilar-Manjarrez, 1996; Salam, 2000; Perez-Martinez, 2002; Perez-Sanchez, 2002), the purpose of the questionnaires in this study was different, being used for gathering technical data and information for both scoring and weighting procedures. In contrast to earlier projects, the present study was based on a system in which no alternative productive activities are allowed or could be performed by users different from artisanal fishermen. For this reason, interviewees were selected based on their expertise on the subject matter to collect scientific data, rather than user-preferences. Weights provided by experts were therefore used as guidelines for the assignation of final weights for each criterion and submodel.

In this study, operational factors were weighted higher than those used in the species requirements submodel (60% versus 40%). This was probably the most difficult decision taken when weighting these submodels, and is especially controversial when considering that most studies in Chile have only considered biological and physical factors mostly relevant to the species-specific preferences for optimal growth and survival, not even pointing out operation or technical elements of a restocking exercise when selecting the site for releasing. In this case, weightings were assigned based on knowledge of the study area and production system, supported by relevant information provided by local fishermen and technicians. As for the study area has been historically identified as one of the richest fishing grounds supporting substantial benthic production (Association of Independent Artisanal Fishermen of Quintay, pers. comm.), this indicates favourable conditions for growth and development of sea urchins. This was the main reason why the local association requested this coastal region as major AMEBR. On the other hand, wave and wind-exposure, currents, physical features of the sea bottom and topography, oceanographic and environmental conditions of the region, which mostly determine this relative optimal habitat conditions are also responsible for constraining procedures and operational activities in the coastal zone. These conditions are significantly limiting for fishing, diving, harvesting and transportation along the shore of Quintay. Hence, operational factors may in fact determine the practical implementation, efficient monitoring and long-term success of a restocking programme for sea urchins in Quintay.

In summary, is suggested that having ensured that most critical biotic and abiotic requirements are achieved in a given location, final discrimination between suitable sites should be prioritised on reducing operational risks and implementation practicalities.

The final output CROSSTAB-classification map (Fig. 4.50) shows 16 different suitability¦availability combinations or site categories, ranging from 4¦100 to 8¦100 (suitability points¦availability %). These had an average of 6.44¦69.37 (covering an area of 82.5 Ha overall equivalent to 81.21% of the study area (Table 4.19). The remaining 21.5 Ha (18.79% of study area) represent areas unavailable for restocking sea urchins as they are either covered by major substocks of "loco"-abalone or constitute suitable and covered substrate for keyhole limpets.

This site classification demonstrates high heterogeneity between options, and reveals the full variety of alternatives for decision-making. More importantly, the generally high suitability indexes as well as available area emphasise the prospects for restocking sea urchins in this study area.

Using this valuable information on all the options for siting a seeding exercise, final site selection may only rely on the decision–maker or modeller based on local knowledge or preferences.

In this study, final site selection was based on choosing the ten best sites, considering the best suitability ¦ availability combinations of the pool. A suitability score of 7 was the minimum requirement for inclusion and all categories under this level were excluded (Table 4.20). The remaining options were then reclassified in order of priority (1 to 10) resulting in ten sites aggregated into five best options. Among the final selected options, the higher integrated suitability index is 8 ¦ 100, and 7 ¦ 10 is the least. The selected sites range from 1,380 to 89,466 m^2, with an overall area of 19 Ha approximately, representing 18% of the study area (Table 4.21).

As shown on Fig 4.52, specific locations selected corresponded strongly with those selected by experts, based on their own knowledge and experience. The correspondence in the four upper priority options (categories 7, 8, 9 and 10), where at least one expert identified on each site, and where even the three experts picked the same site, was particularly strong (Table 4.22).

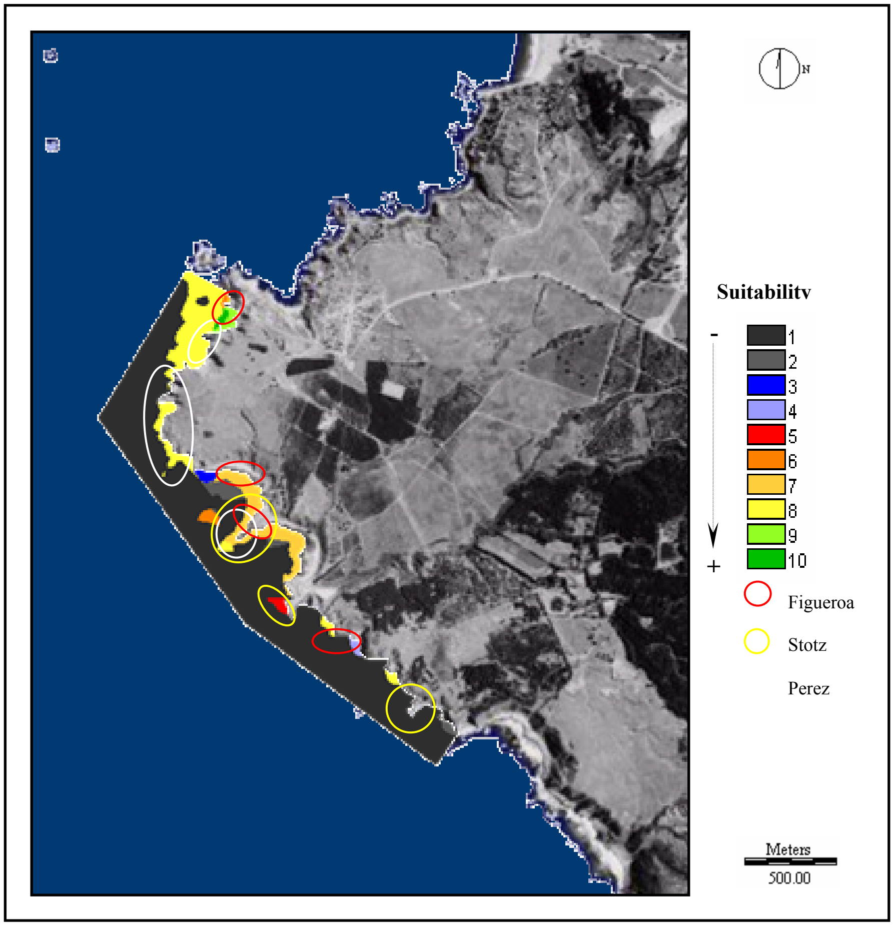


Figure 4.52: Overlay showing restocking sites selected by three different experts in contrast to the final site selection output map of the GISRM.

Table 4.22: Correspondence on selected categories between GIS restocking model and experts.

Selected options by GIS-model	Integrated suitability index	Figueroa, M.	Stotz, W.	Perez, E.
Best option	10	√	-	√
2nd best option	9	√	-	√
3rd best option	8	-	√ (Site 3)	√ (Site 3)
4th best option	7	√	√	√
5th best option	6	√ (Site 1)	-	-

The correspondence between the GIS model selection and both the first and third expert, on the first and second best priorities (site categories 9 and 10 on the very North of the study area) is also very significant. These two sites have an area of 3,921 and 5,331 m^2, representing 4.88% of the overall sites selected.

Moreover, the area covered by these two sites is exactly the location where experimental restocking has been performed by the MRCQ during the past four years (Figueroa *et al.*, 1998). Here, lower intertidal pools and shallow upper subtidal were surveyed and selected for the introduction of 15,000 juveniles in 1998, which were monitored and sampled during a 27-month period (Figueroa, 2000). After the approval of the MAP component for the red sea urchin in 2000 (see Chapter 2), these and nearby surrounding sites were reseeded by the local fishing association during 2001, considering the introduction of 85,000 seeds provided by the MRCQ (del Campo and Perez, 1999).

Although the experts identified some priority areas, which corresponded to those identified with the GISRM, they all underestimated the options in comparison with the model here applied. This strongly emphasises the value of the GIS approach as it is logical, and allows identifying all the possibilities. As the model is based on sustainable principles it is particularly valuable and goes well beyond individual selection or preferences. Unsurprisingly, several of the selected sites are located exactly where major substocks naturally occur at the management area. These substocks were located from information provided by local fishermen, and were later confirmed in the pilot sampling carried out during the BLS in 1999 for establishment of major banks for the final assessment. A similar approach, using local fishermen and fishery managers has been used in North Carolina to identify localities having historically supported substantial natural production of clams (Peterson *et al.*, 1995). Only rarely has the extensive traditional knowledge of fishermen adequately been utilised in western science or in application of science for restoration (Johannes, 1976). However, the results arising from this work and long experience at Quintay has shown that a proper combination of local knowledge, GIS modelling for site selection, and on-site evaluation, may be the way to overcome the vagaries of natural site variability, allowing identification of sites likely to sustain best survivorship, growth and long-term development of seeded individuals.

Outputs generated from this study must be also analysed in terms of production, allowing for extrapolation of bioeconomic consequences. Thus, if the estimated mean density of sea urchins in the study area (28 ind/m^2) is considered, the group of selected sites for restocking should be able to sustain a maximum population of 5,320,000 individuals. Even though this figure may seem overestimated in comparison with the natural estimated population (452,000 sea urchins), it is important to take into account that this simple calculation is only based on 18% of the overall area of study. This may imply therefore that this given management area is oversized with respect to the red sea urchin resource. However, this is not the only targeted species of the AMEBRQ, and “loco” and keyhole limpets) are also of commercial interest for local fishermen. The “loco”-abalone is especially relevant as it is the highest valued commercial benthic resource in Chile, whose potential inhabitable area estimated at 1,009,210 m^2, constitutes 97.15% of the AMEBRQ. Bioeconomic extrapolations of spatial outputs of this study must be analysed strictly on the basis of the relative importance of each benthic resource in the system or in terms of their specific contribution to total incomes of the local fishing association. This and other issues related to the bioeconomic implications of the size of management areas in relation to the targeted resources are discussed further in the next chapter.

Final weights and their integration into the model outputs are specific to the modelled system. Weights may distribute differently between determinant criteria and submodels depending on the specific characteristics of the coastal area (e.g.: area, geographic location, accessibility) and resources inhabiting on it (e.g.: distribution and coverage, relative commercial importance) but also as a function of predominating conditions (e.g.: oceanographic, environmental) on the system and conditions of study (e.g.: scale, resolution).

This model was constructed to provide information regarding the suitability of restocking sites, and their availability and extension within the area of management. This constitutes an essential input to be used in the biosocioeconomic simulation model. The spatial submodel attempted to estimate the quantitative allocation of individuals, and the subsequent allocation of the area of each zone, as successive restocking exercises take place. Based upon the optimal initial restocking density the model allows the estimation of the total area required for the seed to be released and also calculates the overall seed capacity of the system, taking into account the selected sub-areas available for restocking.

The use of GIS provides an interactive micro-scale laboratory for site assessment, selection, monitoring and management applied to this or any other cultured species based on restocking or field grow-out (Arnold *et al.*, 2000). The GIS methodology used in this study allowed development of an easy-to-use and updateable database, which enabled habitat characterization, identification of species preferential habitats, strategic planning of on-site operations, estimation of effective area availability and site selection for alternative management of targeted resource. The GIS model developed for allocating sea urchins restocking sites offers a flexible, cost-effective, user-friendly and descriptive technique for support decision-making on management of this species and other benthic resources. This constitutes a major contribution to a more clear system, favouring administration, management and communication for and between government-administrators, fishery managers and users within the scheme of AMEBRs for small-scale fisheries in Chile.

CHAPTER 5

RUNNING AND IMPLEMENTING THE BSESM

5.1 INTRODUCTION

5.1.1 UNCERTAINTY AND RISK IN FISHERY SYSTEMS

According to FAO (1995b), potential variability on the overall performance of a fishery system may be determined by a number of uncertainty sources. Major variability takes place in abiotic factors, affecting resource abundance and distribution in temporal and spatial scales, and the effects of ecologic interdependencies (e.g.: competence, predation), which are given by intra and inter specific processes influencing the target specie and the whole community. In addition to this, are variability on prices of inputs and products, producing changes on exploitation intensity and market demand, and variability on fishing effort, produced by the use of differential fishing gears, fleets, and exploitation patterns. Finally, likely variability on resource management measures involving decision-makers also determines the performance of the bio-socio-economic system under analysis.

The overlooking of uncertainty levels and the consequent lack of precaution for management of most open-access fishery systems has caused overexploitation, decline of economic returns and overcapitalisation of fishing fleets (Garcia, 1996). Likewise, many regulated fisheries have collapsed in ecologic and economic terms as a result of the rather risky management applied, underestimating the dynamic behaviour of complex fishery systems (Garcia, 1992; FAO, 1993b; Garcia and Newton, 1994, Clark *et al.*, 1995). Attempting to change the pace of fishery management, FAO (1995b) and the Swedish Government together with a scientific forum established the so-called *precautionary approach* for research and management of oceanic fishery resources. Under this framework, concepts and guidelines for a bio-economic precautionary management were set. Here, *risk* was defined as the probability of occurrence of undesirable event, *uncertainty* as the incomplete knowledge of a process or state of the nature, and *statistic uncertainty* as the stochastic or error associated to various sources, described by statistical methods.

In addition to this, Hilborn and Peterman (1996) identified seven major sources of uncertainty specifically related to resource assessment and management:

- uncertainty on resource abundance, determined by inaccurate estimation of natural mortality rates (Lapoite *et al.*,. in press), and incorrect stock assessments,
- uncertainty on the fishery model, given by the intrinsic error of the conceptual model, its structure and mathematical equations, and the common lack of multi-specific models (Seijo *et al.*, 1997),
- uncertainty of model parameters, characterized by insufficient consideration of likely variation on major biological, fishery, social and economic model input parameters (Seijo *et al.*, 1997),
- uncertainty on the behaviour of fishery agents involved, determined by their response and participation into different regimes, usually assumed to be a positive reaction towards the management approach (Rosenberg and Brault, 1993),
- uncertainty of environmental conditions, representing a key factor influencing the spatial and temporal abundance and distribution of target species,
- uncertainty on future economic, social and political situation, represented by market dynamics determining product prices, input costs, and also by the local and regional political environment and the social conditions of the fishing communities, influencing the fishing effort dynamics, captures and resource abundance, and
- uncertainty of prospective objectives of administration, which may vary according to the resource dynamics, user preferences, and goals of the whole fishery system.

5.1.2 SENSITIVITY ANALYSIS

Sensitivity analysis (SA) is the study of how variation in the output of a model (numerical or otherwise) can be apportioned, either qualitatively or quantitatively, to different sources of variation or uncertainty, and how the model depends upon the information fed into it (Saltelli, 2000). On this basis, SA constitutes a prerequisite for model building in any setting, be it diagnostic or prognostic, and any field or subject.

Good modelling practice requires that the modeller provide an evaluation of the confidence in the model, by assessing the uncertainties associated with the modelling process and the outcomes of the model itself (Saltelli, 2000). Hence, even though originally created to deal simply with uncertainties in the input variables and model parameters, the uses of SA have been extended to incorporate model conceptual uncertainty, i.e.: uncertainty on model structures, assumptions and specifications.

Modellers can conduct SA to determine:

- if a model resembles the system or process under study,
- the factors that mostly contribute to the output variability and that require additional research to strengthen the knowledge,
- the model parameters that are insignificant and can be eliminated from the model,
- the regions in the space of input parameters for which the model variation is maximum,
- the optimal regions within the space of the factors for use in a further calibration study, or
- if and which (group of) factors interact with each other.

As shown on Fig. 5.1, to perform a sampling-based SA one starts by defining one or a series of candidate models to answer the question considered, and selecting factors for the analysis, including the input and the output variables. Then, distributions must be identified for uncertain input factors.

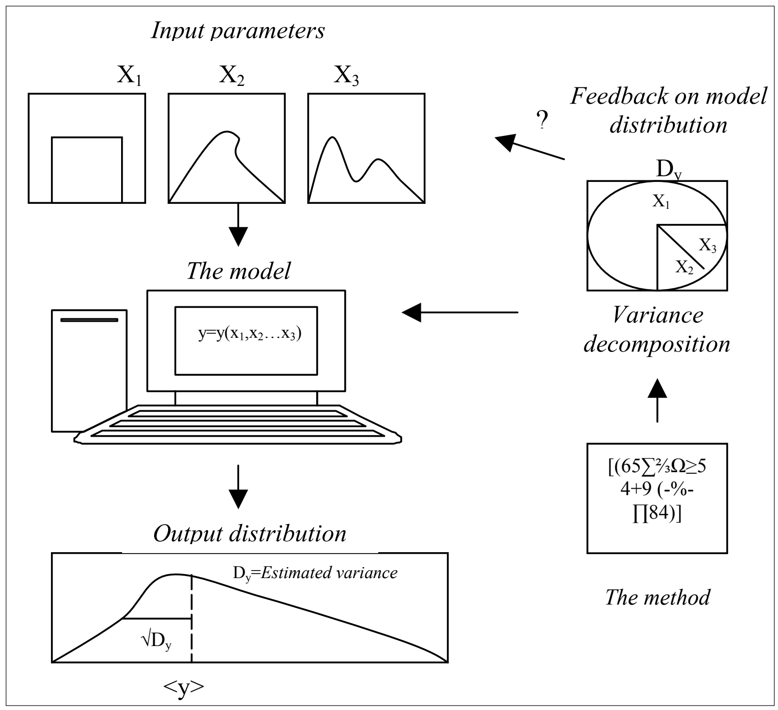


Figure 5.1: A schematic view of a sampling-based sensitivity analysis (redraw from Saltelli (2000)).

If a correlation structure is specified for input factors, realizations can be generated from the multivariate input distributions using *ad hoc* sampling procedures. Next, as the sample is fed through the model, i.e. the model is run repeatedly to produce an output sample, this can be used to built an empirical probability distribution for the response variables. Finally, in order to apportion the uncertainty according to the source (factors), a possible representation of results could be a pie chart that partitions the variance of the output or a distribution of values for the effect variables. In this way is possible to test the model's robustness to variations in assumptions, and observe the likelihood (risk) of undesirable results, as well as favourable results (opportunities) (Anonymous, 1999).

There are different approaches to SA and a very large number of techniques available on specialised literature and proceedings (JSCS, 1997; RESS, 1997; SAMO, 1998; CPC, 1999). Also, there are specific software available for performing SA that use different sampling strategies, all of which are provided within commercially available software.

5.1.3 DECISION CRITERIA AND RISK-MANAGEMENT

As a result of sensitivity analysis, risks and opportunities can be identified and quantified, showing the whole range of possible variation between most optimistic and pessimistic scenarios for the system behaviour. However, fishery managers cannot be optimistic, and assume that the best scenario will take place.

Regardless of the field of application, the ability to define what may happen in the future and choose among alternatives lies at the core of the manager's decision-making process (Saleh and Myrtveit, 2000). Considering that the occurrence of uncertain events may involve more than one possible output scenario, the bio-socio-economic analysis must be ultimately focused on producing alternative strategies, identifying and quantifying the level of uncertainty associated to their application (Seijo *et al.*, 1997). This implies the adoption of decision criteria under the consideration of the risk related to each management alternative.

In many situations in fisheries (e.g.: Hilborn and Walters, 1992), and resource management in general, decisions involving uncertainty are made by using formal decision analysis (Bostford *et al.*, 1999), comprising:

- first the evaluation of how the system of interest responds to various management options under a variety of reasonable assumptions regarding the possible state of nature, and
- then the comparison of how well each decision performs across the range of possible states of nature.

Decision criteria under conditions of risk and uncertainty can be applied to virtually any bio-economic model. At this point is possible to incorporate uncertainty on biological parameters depending on environmental variability, or alternative hypotheses regarding resource and fishing fleet dynamics (Seijo *et al.*, 1997). Different states of nature can be considered for critical parameters, e.g.: natural recruitment, instantaneous mortality rates, price of the target species, as well as for the fundamental bio-economic processes, e.g.: spatial heterogeneity degree, spatial allocation of the fishing effort, returning different performance on biological and economic variables of the fishery while considering either alternative decision *D1, D2,…,Dn* (Seijo *et al.*, 1997).

Within this framework, 'risk management' could be defined as a systems dynamics optimisation process, which objective is finding the most robust policy under variation in the underlying model risk-factors (policy robustness) (Saleh and Myrtveit, 2000). Through this process, the system dynamist may find a way to define what may happen in the future, experiment with various scenarios, choose among alternatives, and develop the best long-term strategy, such as different management regimes for a given benthic resource or commercialisation strategies of the final product.

5.2 OBJECTIVES

The aim of the following sections was to test, run, implement and evaluate the application of the BSESM within a real system-based framework. Consequently, the target of this process was first to check the underlying theories, structure and operation of simulation model on the basis of real data, represented by the case study. Then, run it to project and describe the biological effects on the stocks, socio-economic consequences for fishing community and the spatial dynamics of the coastal areas, resulting from the application explicitly defined management plans. The following stage was aimed at the design, search, finding and analysis of policies forming up strategic plans for management of the red sea urchin fishery at the study area, carrying out a sensitivity analysis and objective-orientated optimisation-based risk management routines. The aim of the final stage was to put into practice, appraise the application and project the prospective use of the BSESM in the real system, i.e.: at a fishing cove currently operating under the system of AMEBR for management of a red sea urchin fishery. In order to tackle these aims, the objectives of this chapter were defined as follows:

- To test the mathematic structure, computerised implementation and actual operation of the BSESM, and run the software using the case study-based data and information.
- To test the sensitivity of system objectives to potential variability and uncertainty of potential critical assumptions of the model.
- To search for optimum policies robust to changes in critical assumptions, and propose strategic plans for long-term management of the red sea urchin fishery at the study area.

- To assess the overall practical application of the simulation model in the real system and project its prospective wider effective implementation in the fishery administration regime of AMEBR in Chile.

5.3 MATERIAL AND METHODS

5.3.1 THE PLATFORM SOFTWARE FOR MODEL OPTIMISATION AND ANALYSIS

Though model testing and case study-based run was carried out on Powersim Constructor®2.51, optimisation and analysis of the model created was done using Powersim Solver® 2.0. This software provides tools for tuning, optimising and analysing models. When an online model is built using Constructor, Solver can be used to automatically search for optimal decisions and investigate relationships and risks represented in the model (Anonymous, 1999). The software allows performing four major tasks to be referred as: tuning, optimisation, risk assessment and finally risk management.

The *Tune* task (Fig. 5.2) allow the model to be calibrated to historical data and suggests values for calibrator variables to make the model produce simulated results that match observed reference data as closed as possible.

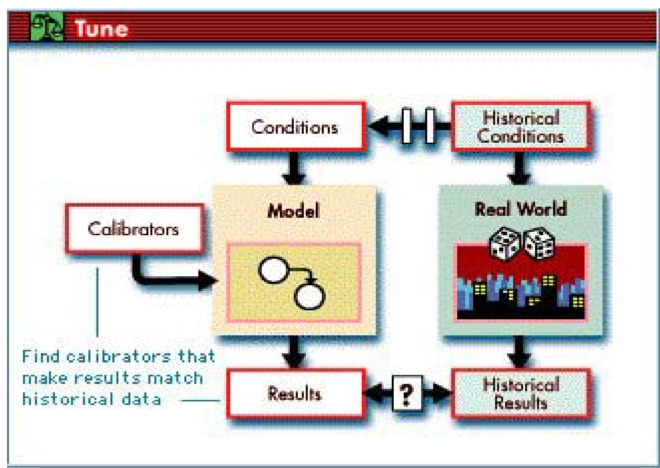


Figure 5.2: The tune task process in Solver® 2.0 (extracted from (Anonymous, 1999).

Further to the this task, the following terminology is applied:

- *Calibrator*: Changeable variables that reflect relationships in a model
- *Conditions*: Values applied when historical data were recorded.
- *Historical results*: Values measured in field or real world, or tuning targets.
- *Results*: Outcomes generated from the model.

Secondly, the *Optimise* task (Fig. 5.3) automates the search for optimal decisions that produce the best results possible. It finds optimal values for decisions, and computes a measure for the distance between simulated results and specified objectives.

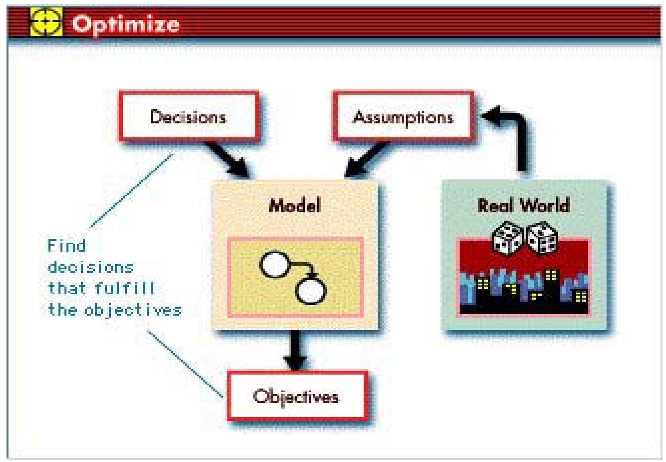


Figure 5.3: The optimise task process in Solver® 2.0 (extracted from (Anonymous, 1999).

When using this task, the following terminology was considered:

- *Decisions*: Changeable variables controlled by the user to meet the objectives.
- *Assumptions*: Changeable variables beyond the control of the user.
- *Objectives*: Target values for the optimisation process.

The *Assess risk* task (Fig. 5.4) tests the model sensitivity to disclose risks and opportunities, which are external to the system itself. Through this task, it is possible to investigate what effects uncertainties on assumptions have in results. In addition, it finds the probability distributions for the simulated results, based upon specified uncertainties in the inputs.

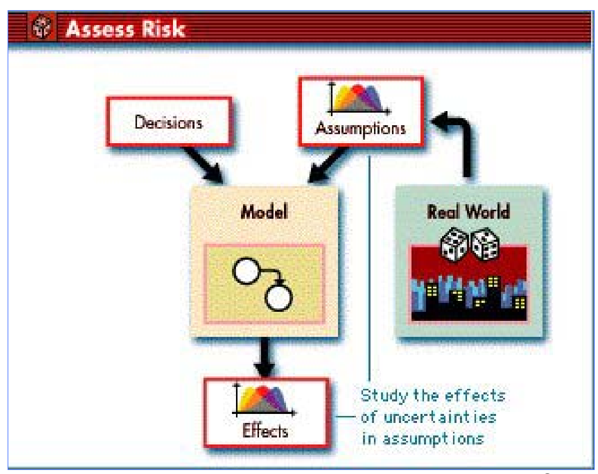


Figure 5.4: The assess risk task process in Solver® 2.0 (extracted from (Anonymous, 1999).

Within this task was introduced a new term:

- *Effects*: Computed variables that show what effects the uncertainty distribution defined in the assumptions have on the results.

Finally, the *Manage risk* task (Fig. 5.5) allows the user to achieve the objectives while controlling risks. Thus, it will find decisions that make the model produce good and robust results and assures that objectives will be met with a certain level of confidence.

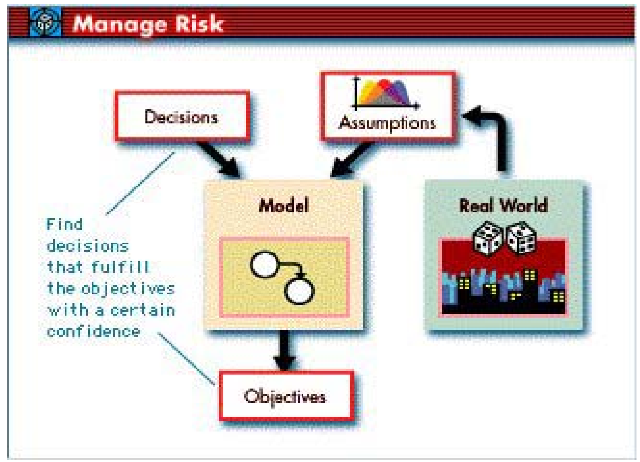


Figure 5.5: The manage risk task process in Solver® 2.0 (extracted from (Anonymous, 1999).

5.3.2 INPUT PARAMETERS DATA, SOURCES AND MANIPULATION

Wild stocks population data

Population data of wild stocks in the study area was extracted from the Base Line Study (BLS) project developed at the AMEBRQ (del Campo *et al.*, 1999). From this report, specific data regarding the size-frequency and population distribution among major substocks were processed to produce the age distribution input data (Input windows 1 and 2), describing the existing stocks in the management area.

Size thresholds were calculated on an annual basis using the Von Bertalanffy individual growth function (VBGF) (Table A.4, Appendix 2), and the total number of individuals on each threshold was assumed to belong to the same ageclass. As the size distribution was originally based on the total population, the number of individuals per ageclass on each substock was proportionally distributed according to their relative contribution into the total population (Table 5.1). Accordingly, the size distribution was therefore rearranged into age distribution to input in the model.

Biological parameters of the species

Growth parameters (k=0.175 $year^{-1}$ and L_{inf}=130 mm used in the VBGF) for the red sea urchin were gathered from relevant studies on the Chilean red sea urchin in the central-north coast of Chile (Stotz *et al.*, 1992). These parameters were used in the estimation of size thresholds defining the annual ageclasses in the population structure, and also in the 'linearized catch curve analysis' used to estimate mortality rates from size-frequency data, as described below.

The exponential natural mortality rate (M_R=0.439 year^{-1}) for released individuals was directly estimated from the report on experimental restocking of hatchery-reared juveniles in the Quintay Bay (Figueroa, 2000) (Table A.5, Appendix 2).

The constant instantaneous natural and fishing mortality rates for wild individuals were estimated using the 'linearized catch curve analysis' described by Sparre and Venema (1992), based on length composition field-based data which was obtained from the Base Line Study (Table A.6, Appendix 2). Accordingly, given the set of length-frequency data and the growth parameters K and L_{inf} it was possible to obtain the total instantaneous mortality rate (Z_W=0.862 year^{-1}), and its natural (M_W=0.132 year^{-1}) and fishing (F=0.730 year^{-1}) components specific to the study area (Figure A.4, Appendix 2).

The population structure design parameter ('target catch factor') was defined by the modeller. Here, the rationale was to scale-up (2 times) the commercial target, trying by this way to ensure that having fulfilled the requirements ('target catch'), an equal residual commercial stock would remain in the system.

Reproduction parameters, excepting for natural recruitment, were obtained from particular interviews with relevant experts (Figueroa, pers. comm.), and active involvement in productive processes, during the first fieldwork stage at the Marine Research Centre of Quintay in 1999 (Table A.7, Appendix 2).

Natural recruitment rates for the baseline macro-scenarios were derived using the wild stocks population data, and the fishing and natural mortality parameters previously estimated in order to approximate the recruitment level required to support the existing stocks abundance and population structure. This procedure was carried out running the BSESM with several recruitment inputs in the system until the stocks showed a steady behaviour in time. Here the 'total natural recruitment' level was estimated at 105,000 individuals per year (Figure A.5, Appendix 2).

Baseline macro-scenarios were then run on the basis of two different, but constant recruitment levels (recruitment A and B): one describing the minimum and not limiting level found to support the actual stock (recruitment B=105,000 individuals/year, as previously described), and the other equivalent to half that sum, representing a limiting state of the system (recruitment A=52,500 individuals/year).

Equally, the ‘recruitment target’ of the system was estimated using the same procedure and input values, but this time using a number of recruitment levels (in the ‘total natural recruitment’ input parameter) so as to return a commercial stock approximately equivalent to the ‘catch target’ (167,273 urchins/year) The estimate found, represented the optimum constant recruitment rate (≈165,000 individuals/year) required in the system to support commercial exploitation at the level defined by the socio-economic expectations of the local community (Figure A.6, Appendix 2)..

In addition, potential range of variation for natural recruitment rates were further estimated using various techniques described by Morgan *et al.* (2000), for use on the sensitivity analysis and risk manage stages (Table A.8, Appendix 2). As described in detail in the sensitivity analysis methodology, this estimation was narrowed down to finding the maximum number of recruits potentially settling and entering the fishery. Thus, the maximum possible recruitment (≈200,000 individuals/year) was calculated on the basis of the effective contribution of recruits per unit of area, obtained from the base line study, and the total area covered by the major substocks, and the minimum limit (25,000 individuals/year) was estimated at one eighth of this sum.

Fishing parameters, cove-specific data and bio-socio-economic figures

Fishing parameters, specific data, and bio-socio-economic figures relevant to the Cove of Quintay were obtained by a combination of relevant reports, and fieldwork-based collection using specially designed questionnaires.

The size of the management area (AMEBRQ) was obtained from the report that officially assigned this lease to the local fishermen association.

Specific data regarding the actual ‘fishing fleet’ at the study area, and the average ‘catch rate’ for the red sea urchin were gathered by means of questionnaires applied to local fishermen at the study area, during the second fieldwork stage.

Likewise, capital costs (‘unitary fleet investment’), some of the operational costs, such as the ‘fleet maintenance cost’ and the ‘unitary fishing cost’, product prices (‘national market price’ and ‘international market price’) and incomes data (‘specific resource historical incomes’ and ‘total historical incomes’) at the cove, were also assessed through the use of questionnaires.

At this point, the questionnaire of socio-economic characterization and determination of productive requirements and expectations by local fishing population (Appendix 3) was applied to fifteen out of the nineteen boat-owners registered at the cove. These fishermen were appointed and anonymously queried covering various aspects, ranging from family structure and educational level, employment and activities prioritisation to fishing activities and harvesting operations, fleet characterisation and management and exploitation of benthic resources in the area.

The socio-economic characterization revealed a typical Chilean cove, with a relatively small number of registered fishermen aged between 25 and 65 years old showing an average secondary school level of education (Table A.11, Appendix 3). Here, fishing and diving constitutes the major economic activity, being practiced during ten months and twenty-eight fishing sessions on average throughout the year, for the red sea urchin (Table A.12, Appendix 3).

Further to fishing performance and commercialisation of the red sea urchin, the group described a daily catch rate ranging from 300 to up to 1,000 with an average of 665 urchins/fishing session per boat, which are sold at the beach at a unit average price of $250 and mainly destined to the exportation market (Table A.13, Appendix 3).

With regards to fleet investment and maintenance costs, the inquest disclosed a capital investment ranging from 1.5 to 5.4 million pesos per boat, including diving equipment and fishing gear, and a monthly average cost of $18,000 per boat for periodical repairs. In addition, daily fishing operating costs ranged from $8,100 to up to $35,000 per session (Table A.12, Appendix 3).

For the case study and most coves in Chile in actual terms the fishing fleet is an existing asset that is generated and passed through generations, and capital investment is nil other than the case for a completely new project. Therefore, detailed consideration of initial investment-related costs was not required for formal economic evaluation.

Concerning the historical performance of fishing operations of the red sea urchin fishery, the group described very consistently an average historic catch rate of 1,000 urchins per fishing session. More importantly, the current expectations for the annual catch was estimated at an average of 93,231 urchins, ranging from 21,000 to up to 180,000 urchins per year, standing for an estimated annual income of roughly 23 million pesos (Table A.14, Appendix 3).

Additional data of fixed operational costs, such as the ‘AMEBR tax’, and the ‘fishing opportunity cost’, ‘unitary restocking labour cost’, ‘technical assistance cost’ and ‘seed cost’, were respectively obtained from relevant sources (Diario El Mercurio, 2003) and interviews with experts (Aranguiz; Barrios; Figueroa, pers. comm).

Finally, the rate of return (12 %/year) for financial evaluation of the project was defined according to the criteria established by development banks (including the ADB and the World Bank), obtained from Dixon *et al.* (1986).

Monitoring plan information

Monitoring parameters were adapted from the monitoring programme designed in the MEP and approved for the red sea urchin at Quintay in 1999 (del Campo *et al.*, 1999), from which specific elements, such as the minimum monitoring sessions and the supporting fleet required were taken (for details see Chapter 2).

Restocking programme design parameters

Data specific to technical parameters describing the restocking exercise (‘restocking events’, ‘restocking rate’, ‘supporting fleet’, and ‘restocking density’) were obtained from information gathered from specialists with extensive understanding and experience on restocking programmes at the study area, which were interviewed during the second fieldwork (Perez; Figueroa, pers. comm.). The ‘density reduction’ input parameter estimated at a negative rate of 18.41%/year was processed from empirical data collected from experimental restocking exercises carried out at the study area (Figueroa, 2000) (Table A.9, A.10 and Fig. A.7, Appendix 2).

Additionally, specific data on potential restocking sites (‘restocking sub-areas’) was directly imported from the final outcomes of the GIS-based restocking model (GISRM) (for details see Chapter 4).

5.3.3 MODEL TESTING AND CASE STUDY-BASED RUNNING

Case study input parameters data

Having identified the specific sources of information, quantitative data was gathered, processed and manually entered into the simulation model.

The full list of input parameter values used to run the BSESM for the case study macro-scenarios is given in Table 5.1 and 5.2. Values between brackets represent minimum and maximum limits, between which the expected or average was chosen (in bold).

These figures were used to produce the baseline data set for the case study, which was used for model testing, and subsequently modified for running a number of macro-scenarios, carrying out the sensitivity analysis, and risk management optimisation routines for strategic planning.

Table 5.1: Wild stock ageclass distribution input data used for the case study (processed from (del Campo *et al.*, 1999)).

Input Windows 1 and 2											
Ageclass/Substock	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
1	370	272	257	886	71	1,367	-	-	-	-	3,224
2	8,349	6,137	5,803	19,970	1,595	30,825	-	-	-	-	72,678
3	10,503	7,721	7,301	25,123	2,006	38,780	-	-	-	-	91,434
4	5,824	4,281	4,048	13,930	1,113	21,503	-	-	-	-	50,699
5	5,420	3,984	3,767	12,964	1,035	20,011	-	-	-	-	47,182
6	8,820	6,484	6,131	21,097	1,685	32,565	-	-	-	-	76,781
7	5,925	4,355	4,118	14,172	1,132	21,876	-	-	-	-	51,578
8	4,242	3,118	2,948	10,146	810	15,661	-	-	-	-	36,925
9	1,650	1,213	1,147	3,946	315	6,090	-	-	-	-	14,360
10	505	371	351	1,208	96	1,864	-	-	-	-	4,396
11	168	124	117	403	32	621	-	-	-	-	1,465
12	236	173	164	564	45	870	-	-	-	-	2,051
Total number of individuals per substock	**52,011**	**38,233**	**36,153**	**124,408**	**9,936**	**192,033**	**-**	**-**	**-**	**-**	**452,775**

Table 5.2: Additional input data used for the case study (AMEBRQ).

INPUTS 3	Input parameter	Units	Value
Mortality parameters	Natural mortality wild individuals	$year^{-1}$	**0.132**
“”	Natural mortality released individuals	$year^{-1}$	**0.439**
“”	Fishing mortality	$year^{-1}$	**0.730**
Population structure	Target catch factor	times	**2**
Reproduction parameters	Total natural recruitment	Individuals/year	**52,500…105,000**
“”	Recruitment target	Individuals/year	**165,000**
“”	Sex ratio	%	**50.00**
“”	Fecundity	Larvae/spawner	(700,000-1,500,000) **1,100,000**
“”	Settlement index	%	(15-20) **17.5**
“”	Post settlement survivorship	%	**75**
Fishing	Fishing	Yes/No	**Yes…No**
“”	Catch rate	Units/day*boat	(300-1,000, Max: 2,000) **665**
Cove	Fishing fleet	Fishing units	**19**
“”	AMEBR size	Ha	**104**
Monitoring	Monitoring sessions	Days/year	**2**
“”	Required monitoring fleet	Fishing units/ ha	**0.5**
INPUTS 4			
Costs	Unitary fleet investment	$/fishing unit	(1,500,000-4,500,000) **0**
“”	Fleet maintenance cost	$/fishing unit*month	(5,000-40,000) **18,000**
“”	AMEBR tax	$/ha*year	**29,360**
“”	Unitary fishing cost	$/fishing unit*day	(8,100-35,000) **16,707**
“”	Fishing opportunity cost	$/fishing unit*day	**75,000**
“”	Seed unitary cost	$/unit	**25**
“”	Unitary restocking labour cost	$/labour unit*day	(8,000-10,000) **9,000**
“”	Technical assistance cost	$/ha	**10,000**
Incomes	Total historical incomes	$/year	**88,000,000**
“”	Historical incomes target resource	$/year	**23,000,000**
Product	National market price	$/unit	**250**
“”	International market price	$/unit	**300**
Project	Interest rate	%/year	(10-20) **12**
INPUTS 5-A			
Restocking zone	Integrated suitability index		
1	10	m^2	**3,921**
2	9	m^2	**5,331**
3	8	m^2	**89,466**
4	8	m^2	**18,165**
5	8	m^2	**3,656**
6	8	m^2	**3,340**
7	8	m^2	**3,037**
8	8	m^2	**56,167**
9	8	m^2	**1,380**
10	7	m^2	**5,288**
Total	6	m^2	**189,751** (18.97 Ha)
INPUTS 5-B			
Restocking parameters	Restocking	Yes/No	**Yes…No**
“”	Restocking events	Days/year	(1-12) **2**
“”	Restocking rate	Seeds/restocking labour unit	**3,000**
“”	Supporting fleet	Fishing units	**2**
“”	Restocking density	Individuals/m^2	Optimum: 160- Practical: **700**
“”	Density reduction	%/year	(3.95-59.72) **18.41**

Static and dynamic testing

Having developed the software, computerized model verification ensures that the programming and implementation of the conceptual model are correct (Sargent, 1998), and the programme must then be tested for correctness and accuracy, first using simple tests, and then more specific testing routines applied on each submodel and the overall model. Here, both static and dynamic testing (analysis) was used (Fairley, 1976).

In the static testing, the software was analysed to determine if was correct using such techniques as correctness proofs and examining the structural properties of the programme (equations describing interrelations, units of measure, etc).

Dynamic testing was carried out executing the BSESM under different conditions to determine that the resulting values obtained in the programme and its implementation were correct. For this, the model was run several times using programming stubs (set of data) based on critical values for the case of study. These procedures were applied using a bottom-up approach, i.e.: testing first the submodels and then the overall model. When possible, resulting values were compared with parallel manual calculations on specific equations to investigate input-output relationships and carry out internal consistency checks.

Finally, when required, reprogramming of critical components was done and further testing carried out until the model was fully tested and ready to operate.

Macro-scenarios design for case study-based run

To run the BSESM for the case study, potential scenarios were designed describing the macro-conditions predominating in the system. Macro-scenarios were defined in terms of the major management measures available within the system studied and the software, i.e.: exploitation and restocking. As formerly explained, baseline macro-scenarios were run under two different recruitment settings: the limiting or recruitment A and the not limiting or recruitment B.

To represent the system conditions and analyse its behaviour most realistically, management strategies describing macro-scenarios were set to reflect the real or potential situation in the study area, respectively representing the past, the current, and the future state of management of the red sea urchin in Chile (Table 5.3).

Table 5.3: Macro-scenarios defined for running simulation routines for the case study.

Macro-scenarios	Restocking	Exploitation	Description of the scenario
1	No- all evaluation period	Yes- all evaluation period	Traditional management, where size and seasonal restrictions are applied to resource exploitation.
2	Yes- first 4 years	Yes- 5 year onwards	Restocking program and management plan proposed and currently applied at the AMEBRQ
3	Yes- not restricted	Yes- 1 year onwards	Massive and permanent flexible restocking programme and adaptive exploitation plan

Macro-scenario 1 represented the traditional management approach of the red sea urchin and most commercial benthic resources, which has been and is currently applied in most AMEBR and open-access coastal areas in Chile. This is based on minimum legal size and seasonal restrictions to regulate fishing activities on these resources. No alternative management tools, such restocking or translocation of individuals from other coastal areas are permitted.

The second, and much less common approach contained the key elements proposed for the red sea urchin management at the AMEBRQ in 1999 (del Campo and Perez, 1999), approved by the Undersecretary of Fisheries and applied at the study area since 2000. This programme consists of an initial stock recovery and management phase, and a final controlled exploitation phase. During the first phase successive restocking exercises are performed for a 4-year period, during which no exploitation is allowed. Thereafter, controlled exploitation is applied, using the traditional legal size and seasonal restrictions, with no further releases of hatchery-reared juveniles.

The third scenario, illustrated the potential future situation, where massive restocking is allowed, with exploitation of commercial sized individuals. This reflects an adaptive and flexible management approach variable options for release of hatchery-produced juveniles and varied exploitation patterns and levels, all based on continuing periodic assessment of the state of stocks.

Input parameter values were fixed and uniform for all potential states of the case study. To allow separate runs of the macro-scenarios, three copies of the BSESM were saved, each then entered with all relevant data at specific settings. The case study was then run on the software-modelling platform, Powersim Constructor® 2.51; using manual stepping results saved, and then captured as screen images for later presentation.

5.3.4 SENSITIVITY ANALYSIS

As all of the assumptions could be subject to varying degrees of uncertainty, it was necessary to analyse the extent to which changes in major assumptions might affect the results obtained. This was carried out using the 'assess risk' task available in Solver. By this means, it was possible to analyse potential scenarios, where determinant factors would show a variable pattern of behaviour, and to disclose their specific effect in the economic and/or biological performance of the system.

Selection of macro-scenarios

Two out of the three major macro-scenarios: 1 and 3, were selected for the sensitivity analysis and further simulations at the 'manage risk' stage, since they were considered to be most realistic and probable descriptions for potential management. At the same time these macro-scenarios covered the wide spectrum of options, with two highly contrasting approaches for management.

Selection of potential risk factors

A number of risk factors (critical assumptions) in the model were defined. The 'assess risk' task allows these to be defined as probability distributions rather than specified values. For this, Solver supports several types of statistical distributions, of which the normal (Gauss) is the most common (Anonymous, 1999).

Thus, all biological, socio-economic and productive assumptions were analysed in terms of their intrinsic degree of uncertainty and their relative influence or importance in the system. As a result, most uncertain and/or determinant input parameters were selected and classified as potential critical assumptions to be analysed at this stage (Table 5.4).

Table 5.4: List of assumptions potentially critical in the model.

Input parameters
Natural mortality wild individuals
Natural mortality released individuals
Total natural recruitment
Catch rate
Seed unitary cost
National market price
International market price

Definition of critical assumptions

The potentially critical assumptions or risk factors in the model were then set up as statistical distributions, and a separate sensitivity analysis was run for each of them. The type of distribution for critical assumptions was defined in terms of the possible pattern of variability in the system, either uniform or normal (Fig. 5.6). In the uniform distribution, all values within the specified range are equally likely to occur. Here, it was required to enter minimum and maximum values for the range. The normal distribution is particularly useful, as many random variables of practical interest are normal or approximately normal or can be transformed into normal random variables in a relatively simple fashion (Anonymous, 1999). Here it was required to enter the expected (mean) value, which determined where the peak occurs, and a standard deviation, which determined the width and height of the peak.

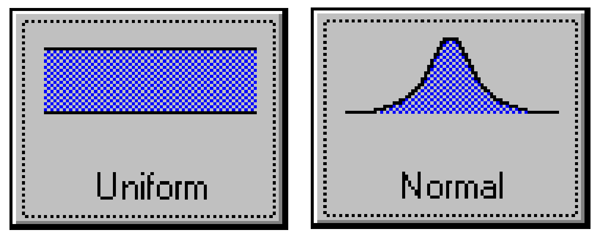


Figure 5.6: Uniform and Normal distribution (extracted from Anonymous (1999))

Ranges of potential variation or uncertainty of critical assumptions were set individually using different data sources and approaches. Table 5.5 shows the complete settings entered for each critical assumption sensitised at this stage.

Table 5.5: Settings for critical assumptions defined for sensitisation.

Assumptions	Definition		Values				Initial value
	Normal	Uniform	Expected	STDev	Min	Max	
Natural mortality wild individuals	√	-	0.132	0.066	-	-	0.132 $year^{-1}$
Natural mortality released individuals	√	-	0.646	0.167	-	-	0.439 $year^{-1}$
Total natural recruitment	-	√	-	-	25,000	200,000	52,500…105,000 individuals/year
Catch rate	√	-	665	279	-	-	665 ind/fishing unit*day
Seed unitary cost	-	√	-	-	0	50	25 $/unit
National market price	-	√	-	-	200	300	250 $/unit
International market price	-	√	-	-	200	350	300 $/unit

For the natural mortality of wild stock individuals, where no supporting data was available, a mathematical approach was used on the basis of a given standard deviation to cover the whole possible range of variation of the assumption round the expected value. Thus, a maximum range of variation of 50% of the average value either side of it (M_W=0.132±0.066 year^{-1}) was used for this parameter.

This limits returned a reasonably precautionary scenario, as the average (M_W=0.132 year^{-1}) and pessimistic values (M_W=0.198 year^{-1}) were considerably larger, and the optimistic value (M_W=0.066 year^{-1}) was slightly smaller than the average natural mortality rates of 0.08 year^{-1} reported for other red sea urchin species in California (Morgan, 1997; Botsford *et al.*, 1999). This parameter value has been widely used in dynamic population models, specifically developed to analyse spatial dynamics in relation to the institution of marine reserves for management of the northern California red sea urchin fishery (Bostford *et al.*, 1999). Furthermore, the percent range of variation used was also fairly safe as compared to the approximately 25% the average of standard deviation estimated from stocking experiments and used for the range of variation of natural mortality of released individuals, as described below.

Thus, for natural mortality of released stock individuals, the average value and its potential range of variation (M_R=0.646±0.167 year^{-1}) was calculated from a number of stocking experiments undertaken at a range of locations in Chile during different periods of time (Table A.5, Appendix 2).

For total natural recruitment, the definition of thresholds of variation was constrained by the extremely high uncertainty associated with its spatial and temporal occurrence and magnitude. Although knowing for certain that natural recruitment had to be accounted as highly uncertain and variable, therefore uniformly distributed, its minimum and maximum level were completely unknown.

The estimation of its distribution was narrowed down to finding the maximum number of recruits potentially settling and entering the fishery. From the results of various direct and indirect estimation techniques applied (Table A.8, Appendix 2), the maximum possible recruitment obtained was 197,512 (≈200,000 recruits/year), being calculated on the basis of the effective contribution of recruits per unit of area and the total area covered (Morgan *et al*. 2000) by the major substocks. Although the minimum value for recruitment among the various techniques used was estimated at 41,000 individuals, representing the actual juvenile population estimated in the Base Line Study (del Campo *et al.*, 1999), an extreme value equal to 1/8 the estimated maximum recruitment (≈25,000 recruits/year) was used to introduce the possible range of variation, i.e.: between 25,000 and 200,000 individuals per year. This approach was suggested when discussing major assumptions in the model structure and operation, and a possible way to tackle them with experts on red sea urchin ecology (Emlet pers. comm.).

The range of possible variation round the average of the catch rate (665±279 individuals/fishing unit*day) was calculated from the information provided by local fishermen on the 'questionnaire of socio-economic characterization, fishing activities and determination of productive requirements and expectations at the Cove of Quintay' (Table A.12, Appendix 2).

Here, local fishermen explained that usually their fishing efficiency during one session could vary between 200 and up to 2,000 urchins per boat, being rather constant for each specific crew depending on their skills, experience and knowledge on localisation of major substocks (Barrios, pers. comm.). Accordingly, this factor would show a normal distribution, where the majority of fishing boats would have the average catch rate, and the minority would have either the minimum or the maximum fishing efficiency.

For the price of seed used for restocking, the range of variability used was between $0 and $50, representing the best scenario at which the restocking material is free, and the worse situation when its cost is double the current average price ($25/unit) at the MRCQ.

As described by Vega (pers. comm.) the current production of red sea urchin juveniles and its market (fishermen associations) in Chile is not stabilized yet. Thus, the offer, demand, prices and trading is not in effect well established, and therefore their behaviour is highly variable and unpredictable. In one hand some fishermen associations have reached positive agreements of mutual cooperation with seed producers, as it is the case of Quintay's fishermen association, whose restocking material has been obtain free of charge. On the other hand, other coves have had to pay for the seed they require at very variable and sometimes high prices depending on a number of factors, such as the volume needed, seed availability, size of juveniles, distance from the supplier, etc.

Wholesale landed prices for benthic resources are usually very changeable, being better described by a uniformly rather than a normally distributed pattern in time. Accordingly, the price of the product destined for both national and international markets was defined as a normal distribution, ranging from $200 to $300/unit for the second, and from $200 to $350/unit for the first and best standard. The ranges of variation for this parameter were gathered from the pricing records of the Association of Independent Artisanal Fishermen of Quintay, and further confirmed with local fishermen at commercialisation points in Caleta Maitencillo and Caleta Papudo, V Region, Chile. These ranges of uncertainty were also reported by Vega (2000) when sensitising the landed prices versus the NPV of a red sea urchin-restocking project at Quintay.

Selection and definition of decisions

The initial values and settings for decision parameters in the model used for sensitivity analysis were kept to evaluate the model's sensitivity under normal operation conditions, and therefore remained as the original input values (for details refer to Table 5.2).

Selection of objectives and risk assessment

When assessing the risk that the changes in assumptions have on the results, three computed effects or objectives were selected (Table 5.6). Selection of objectives was based on both, economic and biological indicators of the system. Selected objectives were the total net present value (TNPV), the total gross incomes (TGI), and the total commercial stock (TCS).

Table 5.6: Computed effects defined for sensitivity analysis.

Objectives
1- Total net present value (TNPV)
2- Total gross incomes (TGI)
3- Total commercial stock (TCS)

The TNPV is the standard criterion used to determine economic attractiveness of a project, which measures the overall size of net benefits (contributions to social welfare) generated by the project (Dixon *et al.*, 1986).

The TGI has been traditionally used to characterise the relative commercial importance of target benthic resources and the sizes of Chilean coves. This criterion provides a well-known and simple indicator of the bio and socio economic performance.

The TCS has also been widely used for population assessment, accepted as a good measure of the state of exploitation of a benthic fishery. It is also a well-known and understood indicator for fishery managers and local fishermen, as it represents the actual stock available for commercial exploitation.

Results obtained from this process were High-Low charts showing the range that the given effect would eventually fall between, with 25% and 95% certainty. In Fig. 5.7 shows as an example a band of lowest to highest output values over time (TCS), as affected by variation in assumption values (natural mortality), where the red and the yellow band represent respectively the 25% and 95% certainty mid-bands. These mid-bands constitute an interval around the mean value within which the outcome values will fall with a given probability.

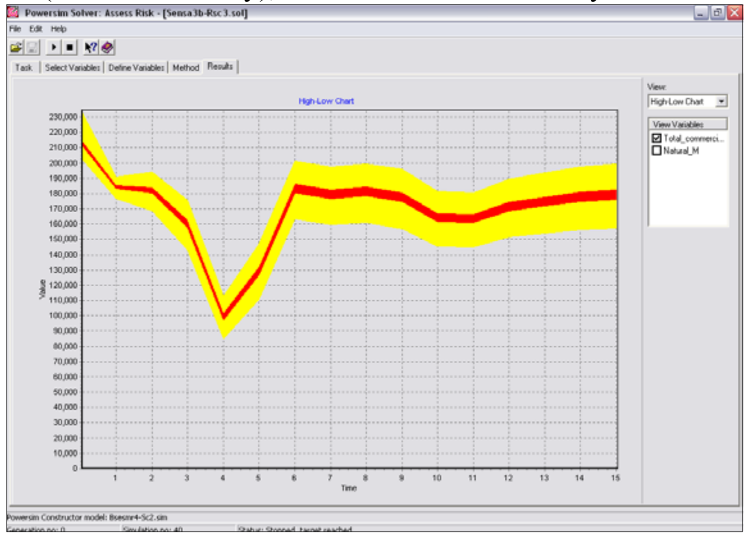


Figure 5.7: Example of High-Low Chart showing the results of the sensitivity analysis for natural mortality as critical assumption affecting the total commercial stock of the population.

Likewise the deterministic runs of macro-scenarios, the sensitivity analysis was run considering two levels of recruitment (recruitment A and B), allowing the examination of the effect of the critical assumptions within the framework of differential recruitment inputs in the system.

5.3.5 RISK MANAGEMENT FOR STRATEGIC PLANNING

By means of the sensitivity analysis it was possible to quantify the impact of a number of potential critical assumptions on the objectives of the system, showing in fact that a number of factors were actually highly critical and others less crucial. Having verified the model critical assumptions and quantified their influence over the system objectives, the ultimate optimisation of management policies took into account these risks.

The methodology used for the risk management for strategic planning was based on the search for specific decision values forming up the policy (sets of decisions) that fulfil the productive objectives within certain and known ranges of confidence. This led to the need to find out optimal management policies that were most robust to changes in assumptions, i.e.: the best set of decisions to achieve a given objective while keeping the risk below a given threshold.

Reselection and definition of critical assumptions

Critical assumptions represented uncertain external factors, which could not be controlled by the user or resource manager. Having demonstrated the degree of uncertainty of each potentially critical assumption, risk factors in the model were reallocated and defined on the basis of the worst possible scenario. For this, definite critical assumptions were defined as follows (Table 5.7).

Table 5.7: Final critical assumptions considered for manage risk process.

Assumptions	Definition		Values				Initial value
	Normal	Uniform	Expected	STDev	Min	Max	
Natural mortality wild individuals	√	-	0.132	0.066	-	-	0.132 year^{-1}
Total natural recruitment	-	√	-	-	25,000	200,000	52,500…105,000 ind/year
Catch rate	√	-	665	279	-	-	665 ind/fish. unit*day
Seed unitary cost	-	√	-	-	0	50	25 $/unit
National market price	-	√	-	-	200	300	250 $/unit
International market price	-	√	-	-	200	350	300 $/unit

Selection and definition of decisions

When Solver tries to optimise a model, it will select different values for the decision variable, from within the specified range (Anonymous, 1999). Selected decisions were comprehensively defined in terms of their possible minimum and maximum values in the system, and differentially applied to each macro-scenario as required.

Although individual optimisations can be very useful for analysing the relative influence, in a real system the resource manager usually has to deal with a multiple criteria decision-making process, having to make a number of crucial decisions in a combined way rather than individual choices. Thus, risk management was based on a global optimisation, i.e. considering the whole set of decisions all together. Table 5.8 shows the final list of decisions and their settings.

Table 5.8: Set of decisions used for the manage risk and strategic planning process.

Decisions	Setting		Macro-scenario	
	Min	Max		
AMEBR size (ha)	26	104	1	3
Fishing mortality (year^{-1})	0	1.1	1	3
Unitary fishing cost ($/day * fishing unit)	8,100	35,000	1	3
Fleet maintenance cost ($/ fishing unit * month)	5,000	40,000	1	3
Monitoring sessions (days/ year)	1	12	1	3
Required monitoring fleet (fishing units/ ha)	0.1	5	1	3
Unitary restocking labor cost ($/ labor unit * day)	5,000	15,000	-	3
Restocking events (days/ year)	1	12	-	3
Restocking rate (seeds/restocking labor unit)	1,000	6,000	-	3
Supporting fleet (fishing units)	1	10	-	3

Selection, weighting, timing and confidence setting-up for objectives

The objectives for managing risk were equal to those defined for the sensitivity analysis stage. However, when setting a 'manage risk' task it was also possible to define a:

- target value;
- time to achieve the objective;
- differential weight to each objective, and
- a confidence level, as a way to look for the objective to be fulfilled with a certain confidence level.

The optimisation process was designed on the basis of a multiple objective-based approach, considering the three major objectives simultaneously. The ultimate optimisation (strategic planning) was based on a trade-off analysis and feedback process, which was focused on the search of the best set of decisions for the achievement of an optimum balance amongst the major objectives defined. This was approached using differential weights of importance for each objective and analysing the outcomes of the model to re-define relevant weights and search for the most robust policy.

As shown on Table 5.9, in addition to settings previously described, explicit confidence levels were set up for each objective. Here it was thought that an 85% level of confidence represented a practical threshold value, ensuring the accomplishment of objectives while keeping risks at low levels.

For the TNPV the target value was set to be larger than cero. This setting represented the minimum requirement for the project to be profitable in economic terms. The TGI target was set to be larger than the historical of incomes generated from the red sea urchin fishery at Quintay, estimated at 23 million pesos per year as derived from the outputs of the questionnaire of socio-economic characterization and determination of productive requirements and expectations by local fishing population (Appendix 3), and previously used by del Campo and Perez (1999). Considering the original commercial target of the system (167,000 individuals/year) was scaled-up two times, the target for the TCS remaining in the system, after exploitation is applied, was set to be at least larger than approximately half this stock (85,000 individuals/year).

Table 5.9: Objectives settings defined for manage risk runs.

Multi Objective (1,2,3) Settings	1:Total net present value (TNPV)	2:Total gross incomes (TGI)	3:Total commercial stock (TCS)
Value (Individuals- $)	>0	>23,000,000	>85,000
Weight (%)			
a. - 1:2:3=0.33:0.33:0.33	33.00 (11.11 each)	33.00 (11.11 each)	33.00 (11.11 each)
b. - 1:2:3=0.50:0.33:0.16	50.00 (16.66 each)	33.33 (11.11 each)	16.66 (5.55 each)
c. - 1:2:3=0.50:0.375:0.125	50.00 (16.66 each)	37.50 (12.50 each)	12.50 (4.16 each)
d. - 1:2:3=0.50:0.40:0.10	50.00 (16.66 each)	40.00 (13.33 each)	10.00 (3.33 each)
e. - 1:2:3=0.50:0.45:0.05	50.00 (16.66 each)	45.00 (15.00 each)	5.00 (1.66 each)
At time (years)	5; 10; 15	5; 10; 15	5; 10; 15
Confidence level (%)	85 each	85 each	85 each

Setting up and running 'manage risk' routines

Powersim Solver uses a combination of optimisation (evolutionary search) and risk management (Latin Hypercube) method to find optimal decisions within a given confidence level. However, these are very time-consuming tasks, because of the high number of simulations performed (Anonymous, 1999). For this reason, initial runs were less accurate and mainly used to evaluate basic effects. Final runs were then stepped up on the number of samples and generations (Table 5.10)

Table 5.10: Settings used for definition of method for risk management stage.

Maximum number of generations	100-300
Total number of parents	3
Number of samples	40
Total number of offspring	15
Minimum convergence rate	1E-6
Seed	100

5.3.6 MODEL APPLICATION ASSESSMENT

To assess the practical application of the BSESM, a field-based protocol was designed on the basis of the following points/objectives of evaluation:

- decision support tools needs diagnosis;
- assessment of technical capabilities, hardware and software;
- determination of the understanding and acceptation degree, and
- operational application assessment.

Covering of these aspects was planned, and then carried out with the local fishermen and fishery managers at Quintay, during a 4-month period in the last fieldwork stage of this research. At this point, a number of presentations, discussion groups, personal interviews and tutorials were held. This protocol was specially scheduled to first introduce the local fishing community with the research problem, second to evaluate the use of the software at their organisation, and ultimately to project its potential future implementation, as a major tool in the system. For this a target group was appointed, including local fishermen, technical unit members, and other fishery managers.

The initial approach to the target group was based on slide presentations so as to generate active contribution and discussion of relevant matters between agents involved. Having gained their interest, the group was gradually introduced into the software fundamentals, assumptions, general structure, and basic operation. Then, the software was set up and installed at the association's administrative office, where the BSESM was shown in operation using real data, based on their cove. Involved agents were trained, through a number of tutorials including all required guidelines to operate and manipulate the software. The simulation model was left fully installed and functional for further evaluation and effective use by local fishing association. During all this process, users were encouraged to provide the modeller with active feedback on any matters they found relevant. The final outcomes obtained from the model application assessment were mostly expressed in qualitative terms, and are presented and analysed on the last part of the discussion section of this Chapter.

5.4 RESULTS

5.4.1 CASE STUDY OUTPUTS

Due to the large number of different outcomes (up to 8 output windows per macro-scenario) produced from running the case of study for the three management alternatives, a selection of major outputs had to be made for presentation and analysis[5.1]. Four output windows per macro-scenario produced the chosen outcomes, numbered as:

- 1, section 'productive targets and results';
- 4 'stocks dynamics' (only for macro-scenarios 2 and 3);
- 5 'population dynamics', and
- 8 'cash flow curve of the project'.

Macro-scenario 1

Under recruitment level A (limiting conditions) productive targets and results for macro-scenario 1 described a management approach that sequentially diminished the commercial stock to less than one forth, and the overall population to roughly half the original number of individuals by the fifth year of operation (upper table on Fig. 5.8). Thereafter, the population slowly reached the balance at approximately 227,000 individuals (Fig. 5.9). This dynamics reflected a population structure well under the expected or desired level required to support the socio-economic requirements of the fishing community, represented by a minimum commercial stock of 167,000 individuals.

As a result of this regime, projected economic returns of the fishing cove increased during the first 4 years, showing a positive and increasing total net present value from the beginning, which tend to become stable thereafter (Fig. 5.14). However, the total gross incomes associated to this development described a constant decreasing pattern until reaching a stable level at 7 million pesos a year. As with the stock condition, this projection was also lower than requirements, defined at an optimum annual gross income of 23 million pesos.

Under not limiting levels of recruitment productive targets and results for macro-scenario 1 described a management approach which returned much better outputs, in terms of both the total population and the commercial stock. With this recruitment level, the commercial fraction almost doubled up reaching a stable level at 107,000 individuals from the tenth year of operation (second table Fig. 5.8), which still was in short supply to support the targets defined.

More importantly, this setting showed the dynamics that would describe the actual population levels and structure existing at the study area. Here, is important to note that the predicted commercial fraction in the population was approximately half the one estimated

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[5.1] Full results are available for further review on the CD provided with this thesis.

on the field-based Base Line Study (equal to the commercial stock at year 0). Rather than an inaccurate estimation, this could be better explained by the positive effect of building up the stock during the recent self-imposed total closure of this fishery at Quintay, for the duration of almost two years up to the date the BLS was executed.

Despite being comparatively better, under recruitment B the economic performance for macro-scenario 1 was not entirely satisfactory. Yet again, although describing an increasing and positive net present value, corresponding annual incomes remained 9 million under the target of 23 million (Fig. 5.14).

Macro-scenario 2

In this case, as restocking was performed at first and exploitation was completely restricted, the total population and its commercial fraction sequentially increased during the first 4 years reaching a peak of 303,00 at year 3 and 313,00 individuals at year 5, for recruitment levels A and B respectively (middle tables on Fig. 5.8). In both cases, this increase was essentially determined by the process of building-up of the stock, due to the initial fishing closure period.

Even when restocking was high as recruitment was limiting (recruitment level A), and released individuals started to join the commercial fraction from the fifth year, the total harvestable increasingly decreased as exploitation was opened from this period onwards. As a result, the restocking programme was not able to support the long-term commercial exploitation of the resource, showing a strong declining pattern of stocks as enhancement was terminated and exploitation initiated (Fig. 5.11).

The population structure and level ultimately reached an equilibrium state approximately equal to the one described by macro-scenario 1, showing however a larger commercial stock throughout the evaluation period due to the fishing closure measure applied during the first four years of operation.

Following a total release of 450,000 juveniles, effective contribution of the four-year restocking programme to commercial stock was minor. Thus, with limiting recruitment conditions, commercial stock of released individuals reached a maximum of 28,000 urchins on year 9 and a minimum amount of 26 urchins remaining at year 15 (Fig. 5.10).

Allowing for both: a limited (A) and not limited recruitment (B) system, economic evaluation showed this management approach to be rather unprofitable, whose payment was negative during the first five years. The total net present value, although showing a constant increasing trend from year 4, only returned positive figures only from the sixth and eighth year, for recruitment level A and B correspondingly (Fig. 5.15). Starting off just after the fifth year of operation, as the exploitation phase took place, the total annual gross incomes were significantly larger than other macro-scenarios, and reached a pick of 40 million pesos for when recruitment was not limiting. Total annual incomes however, showed a strong decreasing pattern that became constant at 7 and 15 million for the recruitment levels A and B in that order.

Macro-scenario 3

Population dynamics for the third macro-scenario were very acceptable in terms of both the overall population and the commercial stock evolution over time, when considering both recruitment levels analysed. This regime returned fairly stable population levels that were comparatively the closest to the stated system requirements.

Under limiting recruitment conditions, total population was always higher than the starting point, and stabilised at 515,000 individuals/year by year 6. Both the total population and the stock were larger than the other management options under the same recruitment conditions (lower Tables, Fig. 5.8). Despite the wild component decreased to half its original level, estimated at 450,000 individuals approximately (Fig. 5.12), the released component progressively developed to achieve a constant and fairly important population of almost 300,000 individuals early on the fifth year of operation. Accordingly, restocking contribution to harvestable fraction was significant in relation with the total size of the stock, ranging from 19,000 to 28,000 urchins remaining every year (lower Tables, Fig. 5.8).

Economic projections showed long-term profitability, with a positive and steadily increasing total net present value, which was lower than macro-scenario 1, but higher than macro-scenario 2. The estimated total gross incomes to be generated from this management alternative were in the majority significantly higher than the other management alternatives, under equal recruitment conditions (Fig. 5.16). However, even these figures did not meet the requirements of the fishing community, fluctuating approximately between 11 and 28 million pesos per year.

Considering the recruitment setting B, macro-scenario 3 proved most consistent population structure, which gradually increased from 450,000 to stabilise at almost 610,000 individuals in total by the seventh year of operation (lower table, Fig. 5.8). Though the total commercial stock level decreased during the first 4 years, reaching a minimum of 47,000 individuals, it turned to be highly suitable thereafter, varying between 92,000 and 122,000 individuals as restocked juveniles joined the fishery from year 5 onwards (Fig. 5.13). This level was stable during the remaining periods, getting close to reaching the expected commercial fraction of the population.

Economic performance showed high long-term profitability, with a positive and steadily increasing total net present value. The project achieved a total net present value of more than 60 million pesos by the final period of evaluation (Fig. 5.16). Additionally, the estimated total gross incomes to be generated from this management approach were higher than the other management alternatives and stabilised at more than 16 million pesos per year, representing the closest alternative to meet the requirements of the fishing community.

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 1; recruitment A*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500
Restocking_target	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500
Total_seed_released	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	50,542	52,409	53,171	53,461	53,568	53,609	53,622	53,618	53,616	53,615	53,615
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	50,542	52,409	53,171	53,461	53,568	53,609	53,622	53,618	53,616	53,615	53,615
Total_population	452,775	342,830	287,795	245,324	220,229	224,702	226,568	227,330	227,621	227,727	227,769	227,781	227,777	227,775	227,775	227,774

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 1; recruitment B*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000
Restocking_target	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Total_seed_released	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	81,506	96,449	102,734	105,356	106,448	106,905	107,093	107,163	107,197	107,214	107,222
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	81,506	96,449	102,734	105,356	106,448	106,905	107,093	107,163	107,197	107,214	107,222
Total_population	452,775	395,330	386,302	384,150	394,388	429,825	444,768	451,052	453,675	454,766	455,224	455,412	455,482	455,516	455,532	455,540

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 2; recruitment A*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500
Restocking_target	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500
Total_seed_released	112,500	112,500	112,500	112,500	112,500	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	19,433	25,470	27,346	27,934	28,139	8,742	2,716	843	262	82	26
Commercial_stock_W	234,740	250,396	290,063	303,938	270,279	272,538	149,923	97,139	73,624	62,963	58,081	55,776	54,656	54,116	53,856	53,731
Total_commercial_stock	234,740	250,396	290,063	303,938	270,279	291,971	175,393	124,484	101,559	91,102	66,823	58,492	55,499	54,379	53,939	53,757
Total_population	452,775	562,039	631,889	676,716	706,400	728,241	499,098	375,620	305,904	265,262	240,982	232,651	229,659	228,539	228,099	227,918

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 2; recruitment B*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000
Restocking_target	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Total_seed_released	60,000	60,000	60,000	60,000	60,000	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	10,364	13,584	14,584	14,897	15,000	4,660	1,448	450	140	44	14
Commercial_stock_W	234,740	250,396	290,063	303,938	270,279	303,502	193,964	146,701	125,519	115,843	111,376	109,247	108,201	107,698	107,455	107,338
Total_commercial_stock	234,740	250,396	290,063	303,938	270,279	313,866	207,547	161,286	140,416	130,843	116,036	110,695	108,651	107,837	107,499	107,352
Total_population	452,775	562,039	644,051	707,378	758,302	801,931	635,594	550,639	504,823	479,162	464,355	459,014	456,970	456,157	455,818	455,671

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 3; recruitment A*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500	52,500
Restocking_target	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500
Total_seed_released	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500	112,500
Commercial_stock_R	0	0	0	0	0	19,433	25,470	27,346	27,934	28,139	28,264	28,599	28,420	28,248	28,113	28,006
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	50,542	52,409	53,171	53,461	53,568	53,609	53,622	53,618	53,616	53,615	53,615
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	69,975	77,879	80,517	81,396	81,707	81,874	82,221	82,038	81,864	81,728	81,620
Total_population	452,775	455,330	472,821	477,107	482,191	506,245	514,602	519,243	519,772	519,156	518,190	517,132	516,001	515,041	514,215	513,479

PRODUCTIVE TARGETS AND RESULTS (individuals/year) *Macro-scenario 3; recruitment B*

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Total_natural_recruitment	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000
Restocking_target	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Total_seed_released	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Commercial_stock_R	0	0	0	0	0	10,364	13,584	14,584	14,897	15,000	15,050	15,148	15,099	15,052	15,014	14,984
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	81,506	96,449	102,734	105,356	106,448	106,905	107,093	107,163	107,197	107,214	107,222
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	91,870	110,033	117,318	120,253	121,448	121,954	122,241	122,263	122,249	122,227	122,205
Total_population	452,775	455,330	484,983	507,768	534,092	579,935	598,226	606,073	608,913	609,849	610,037	609,927	609,680	609,442	609,222	609,018

Figure 5.8: 'Productive targets and results' for macro-scenarios 1 to 3, with two different recruitment levels.

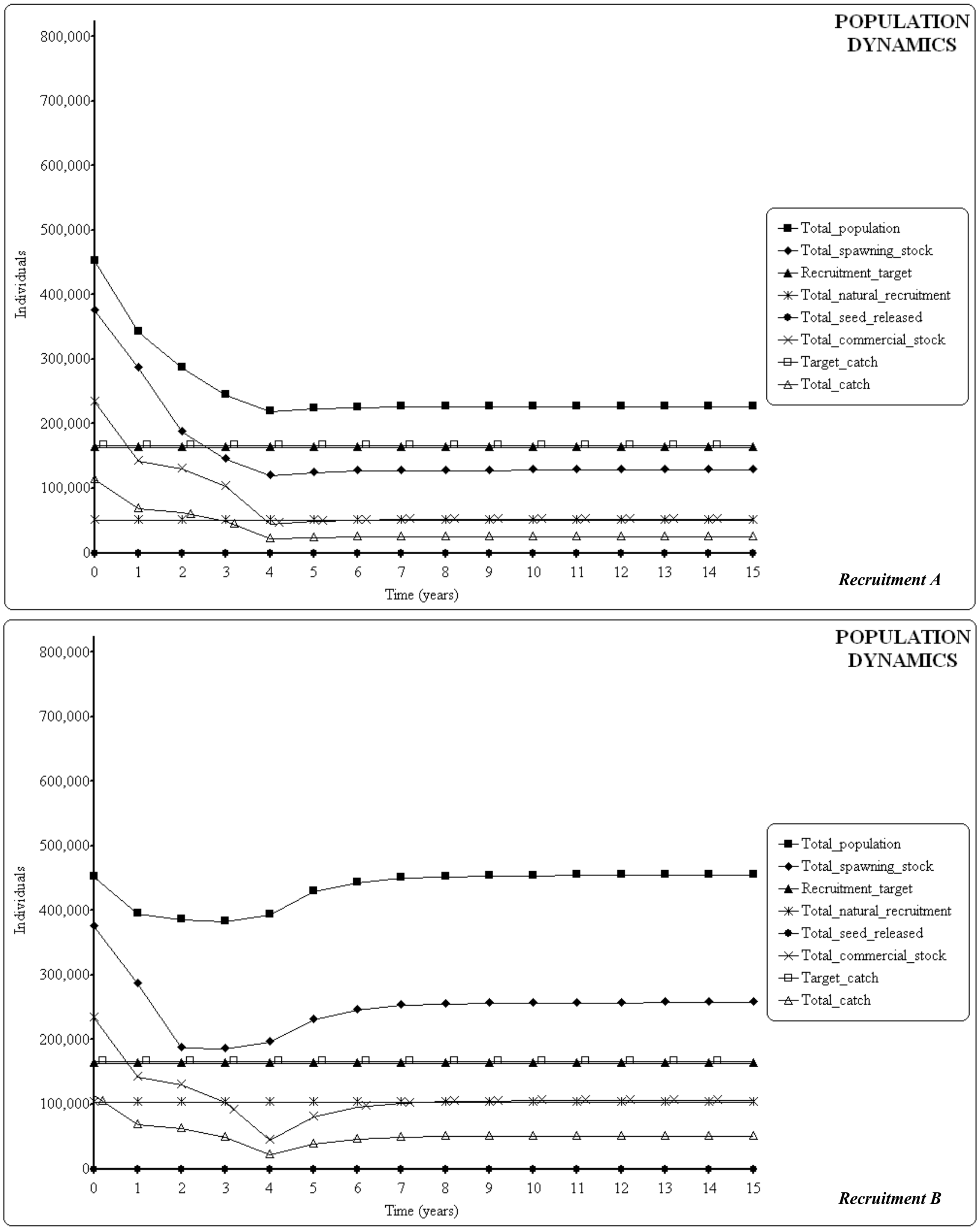


Figure 5.9: 'Population dynamics' simulated for macro-scenario 1 with two different recruitment levels.

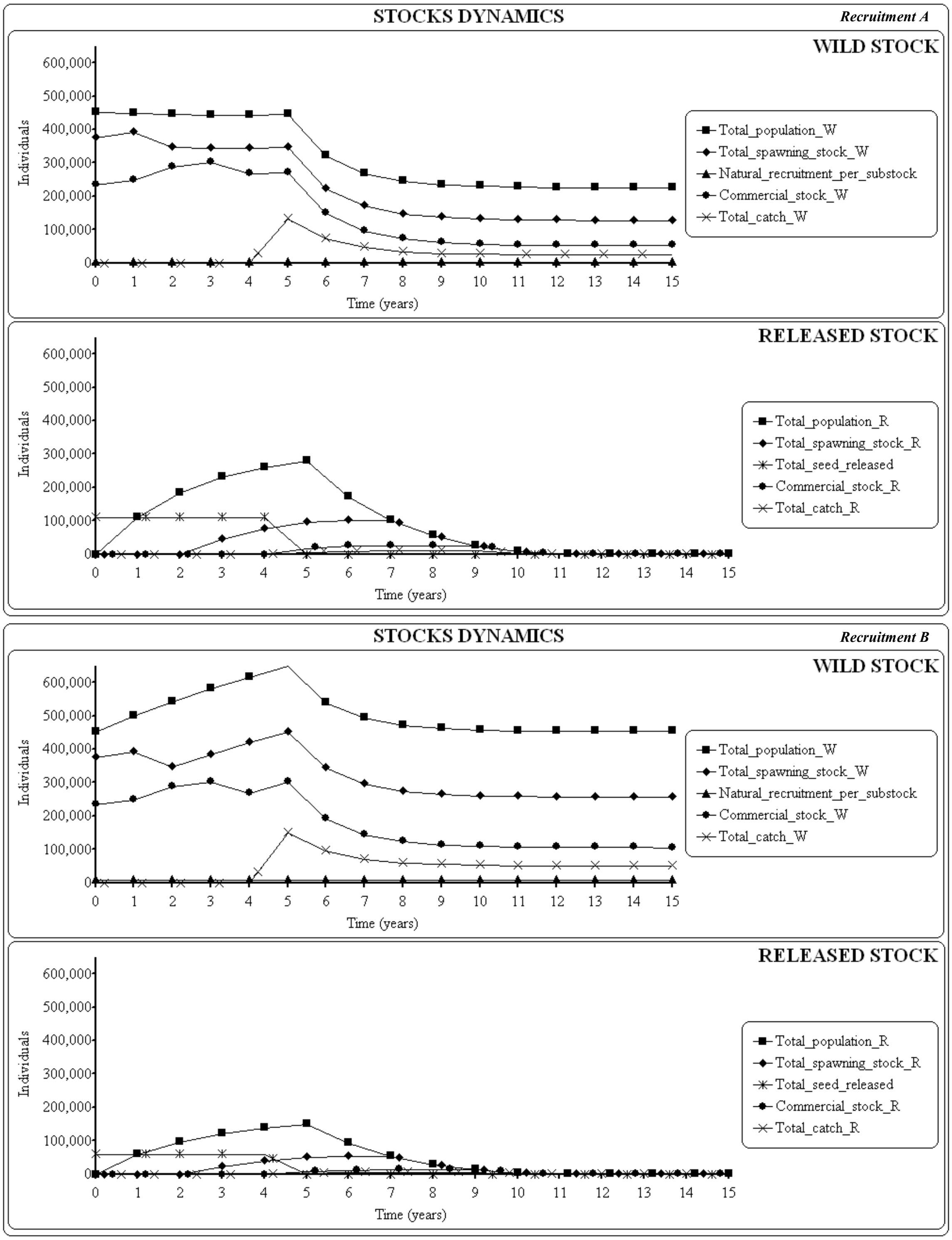


Figure 5.10: 'Stocks dynamics' simulated for macro-scenario 2 with two different recruitment levels.

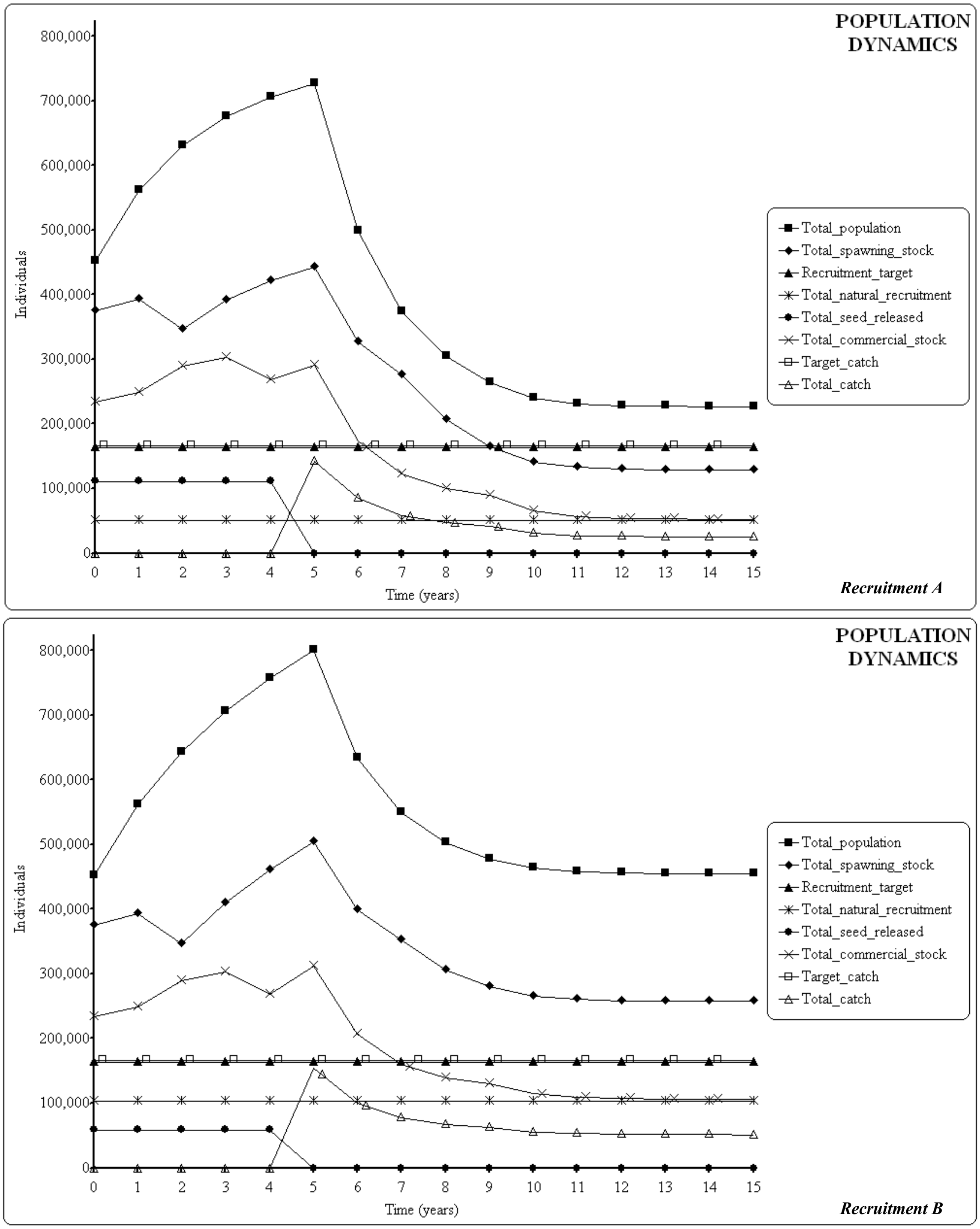


Figure 5.11: 'Population dynamics' simulated for macro-scenario 2 with two different recruitment levels.

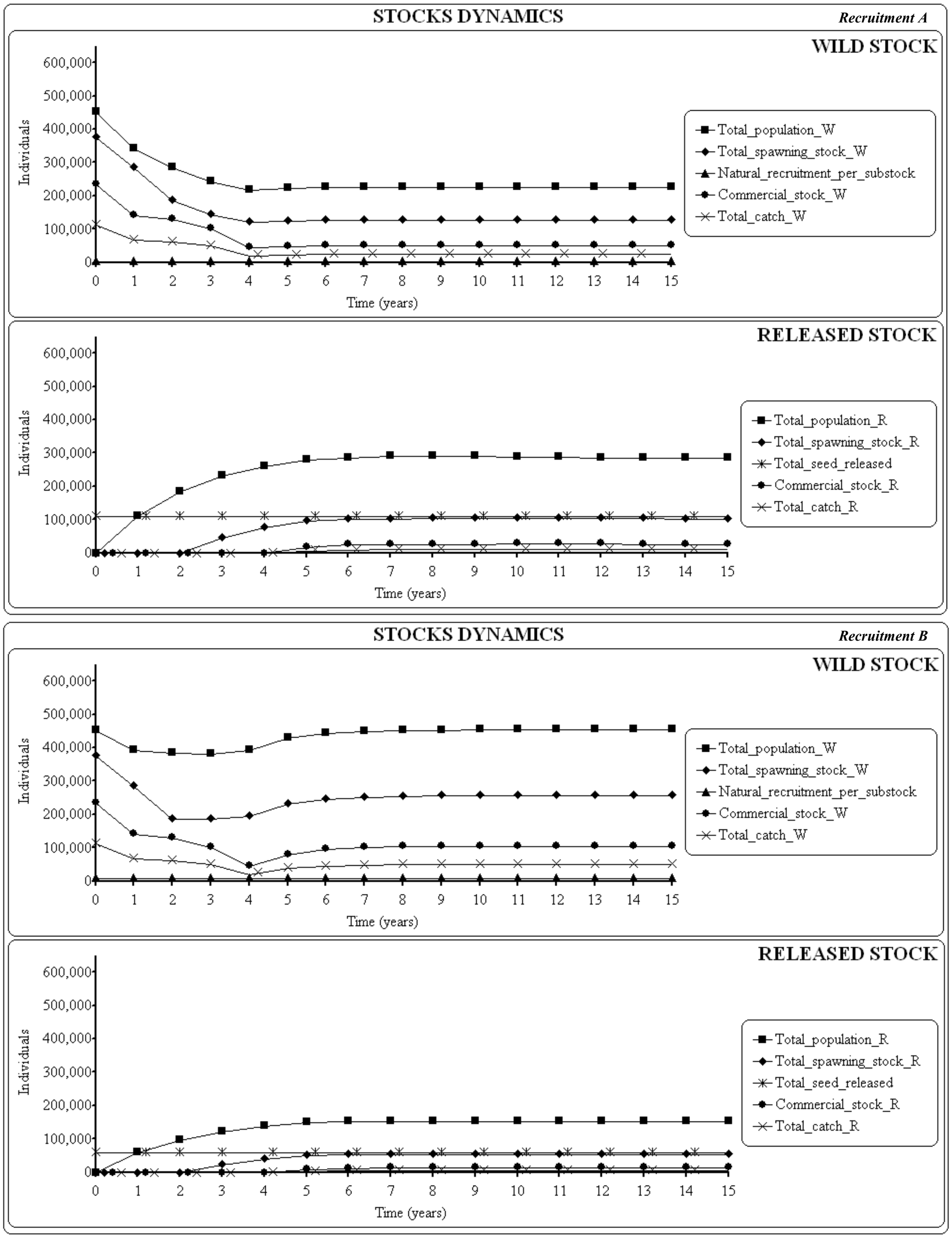


Figure 5.12: 'Stocks dynamics' simulated for macro-scenario 3 with two different recruitment levels.

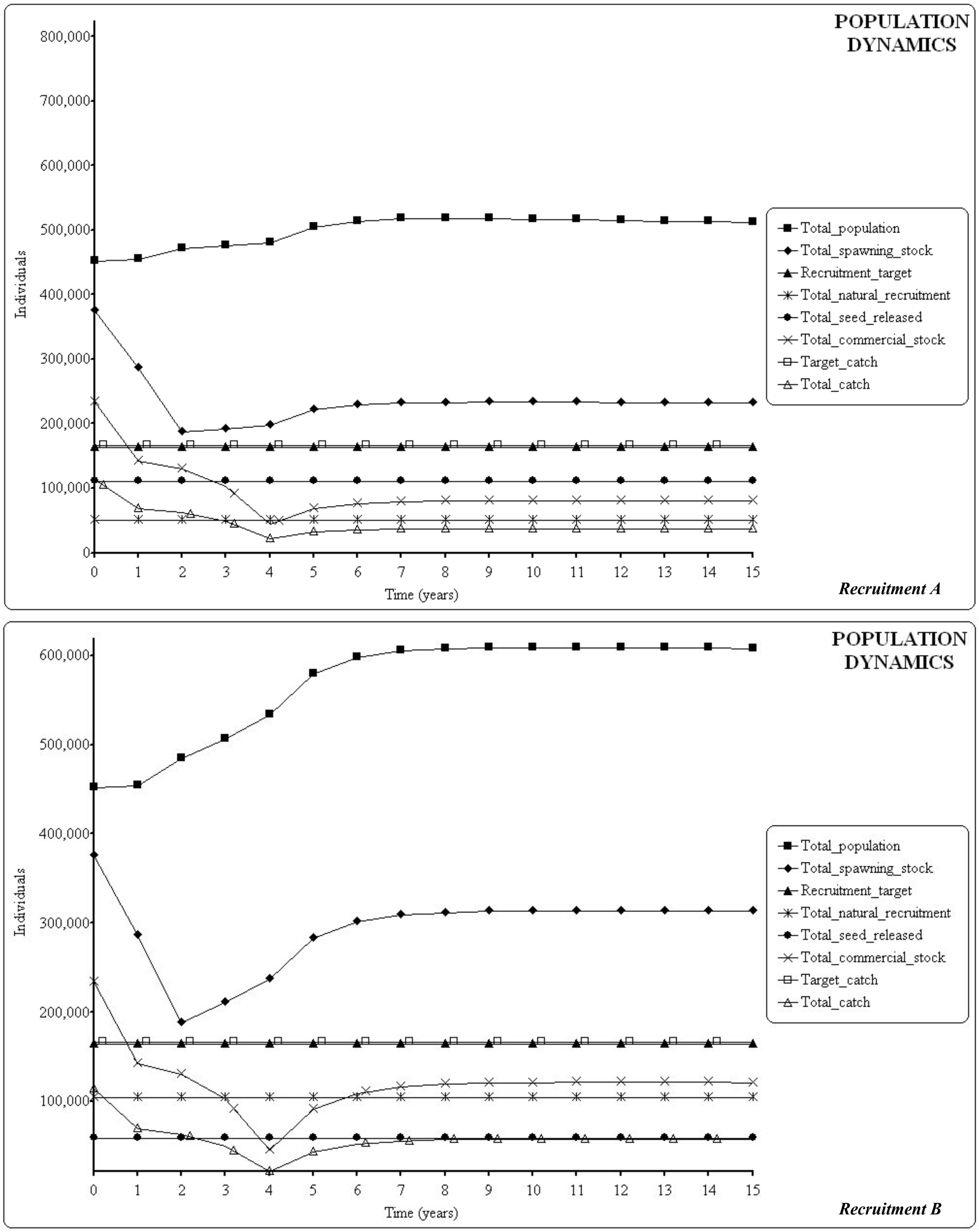


Figure 5.13: 'Population dynamics' simulated for macro-scenario 3 with two different recruitment levels.

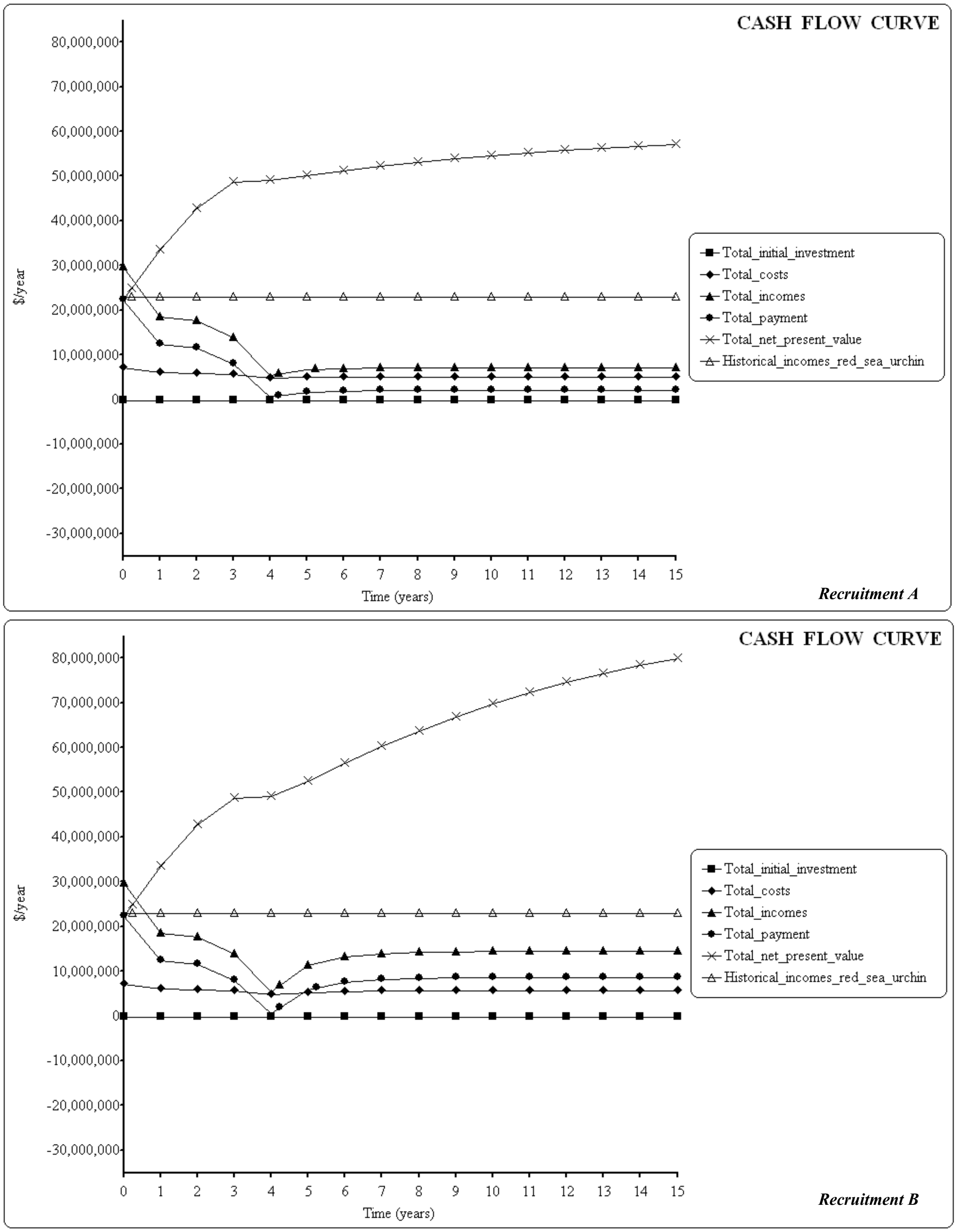
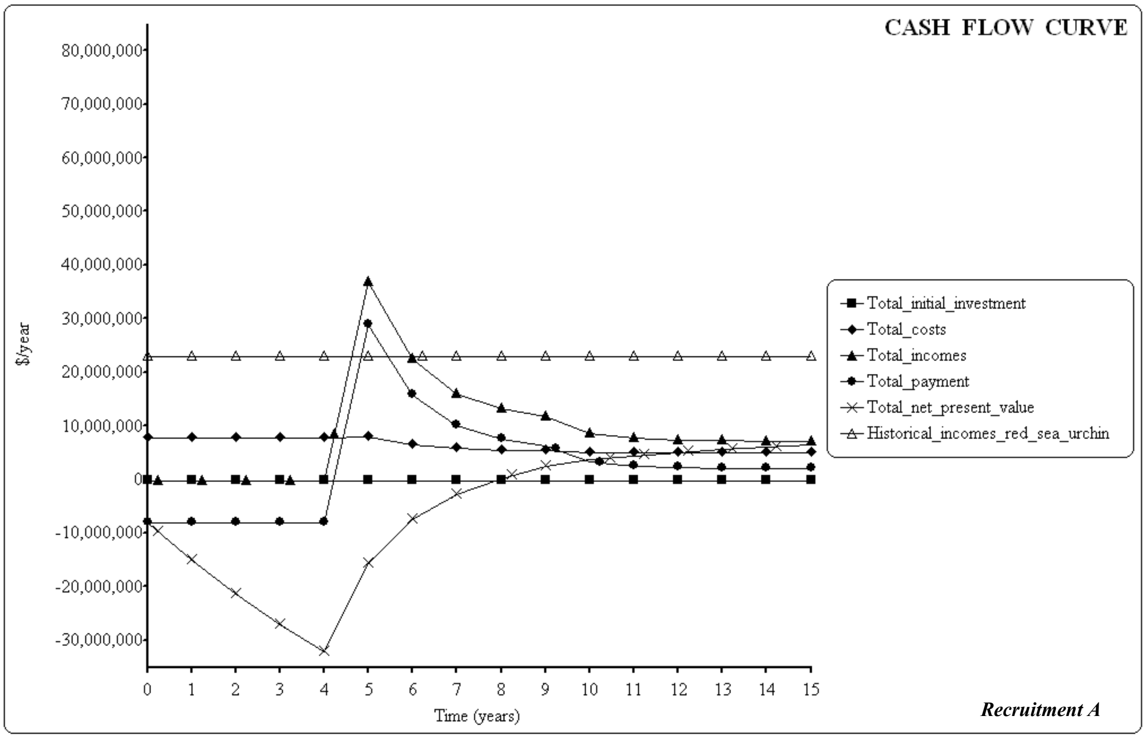


Figure 5.14: 'Cash flow curve' for macro-scenario 1, simulated with two different recruitment levels.



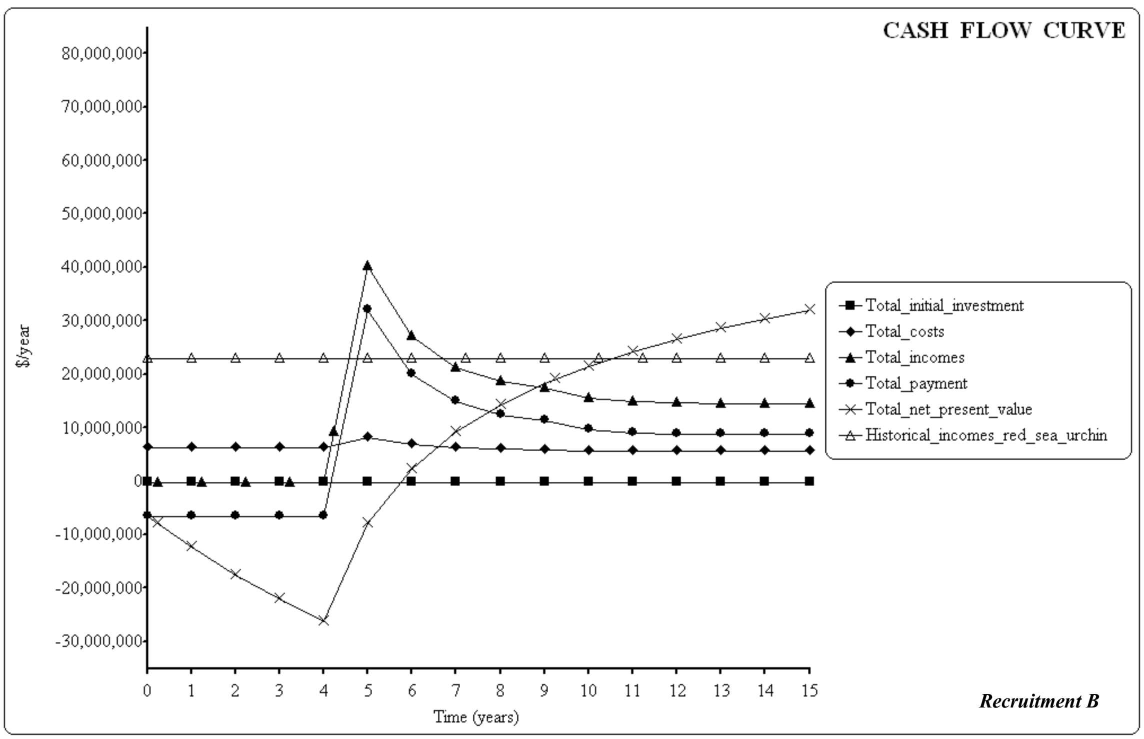
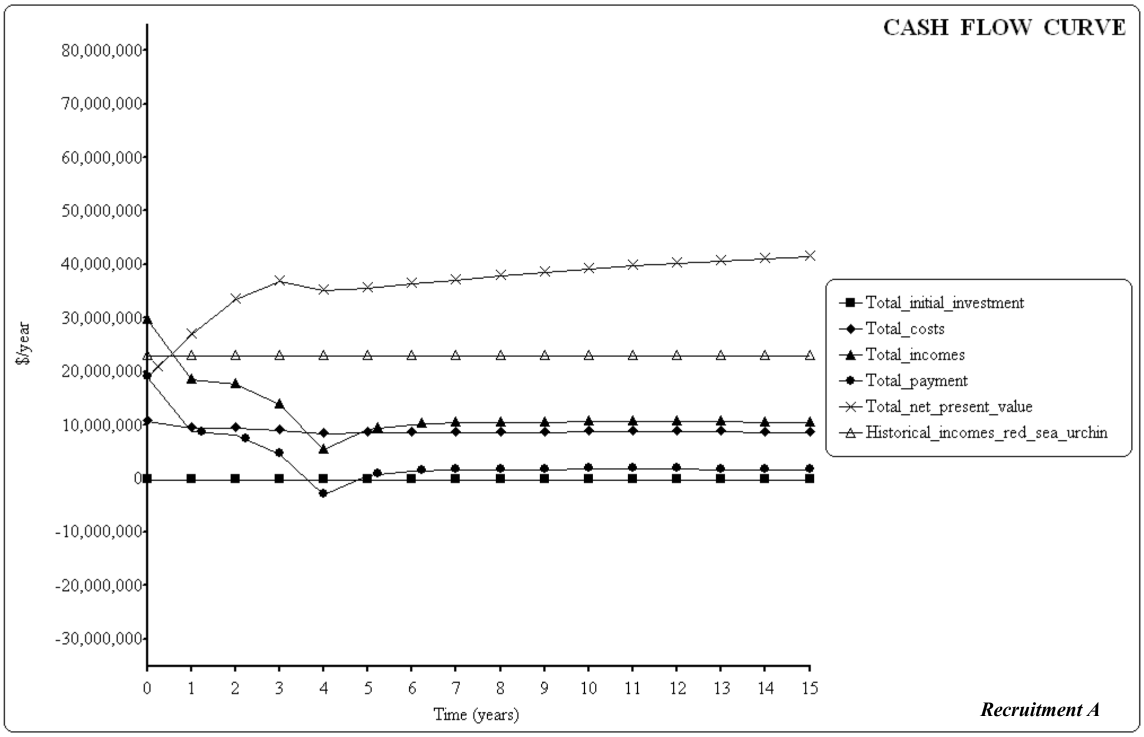


Figure 5.15: 'Cash flow curve' for macro-scenario 2, simulated with two different recruitment levels.



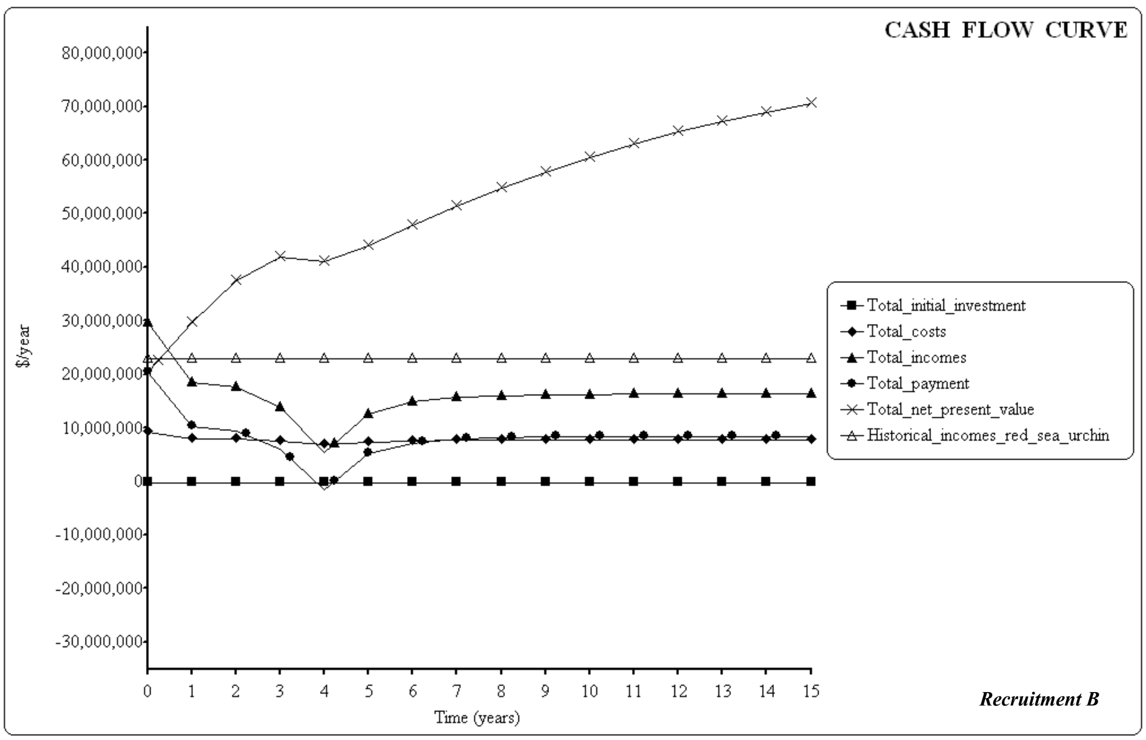


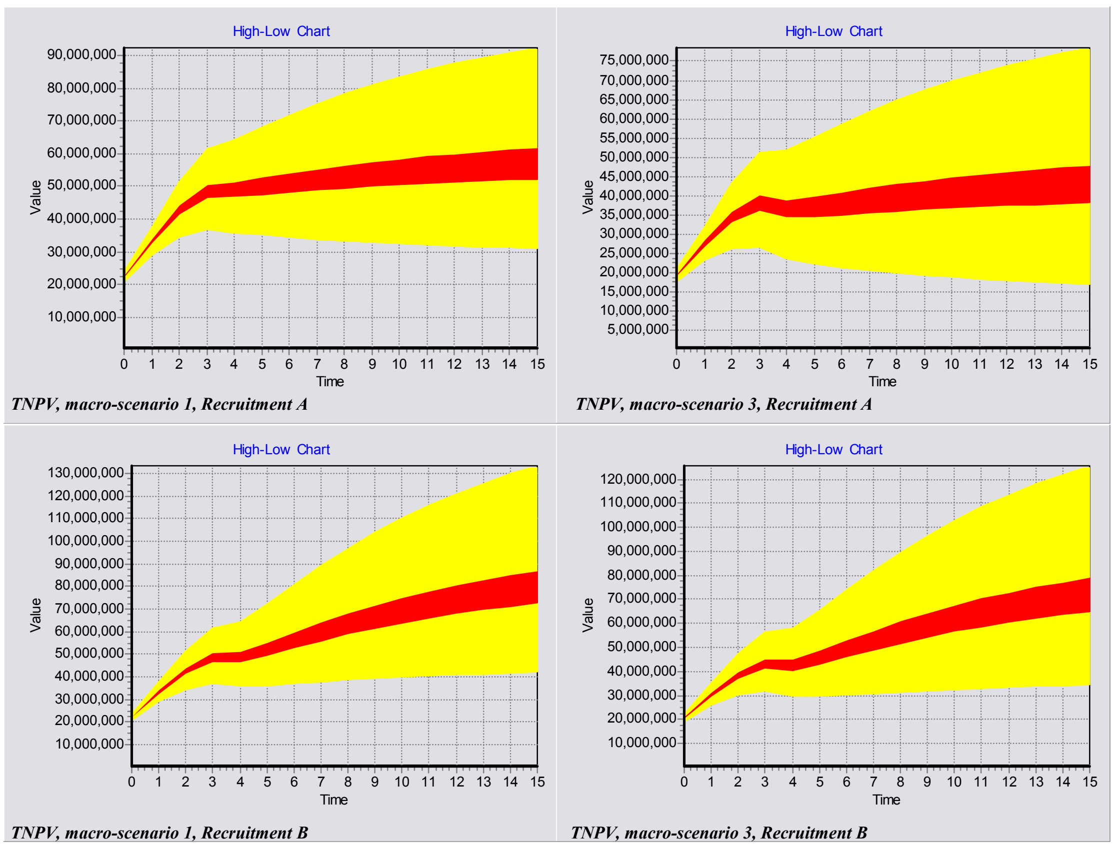
Figure 5.16: 'Cash flow curve' for macro-scenario 3, simulated with two different recruitment levels.

5.4.2 SENSITIVITY ANALYSIS

Final results obtained for the sensitivity analysis of the potential critical assumptions of the model over the targets of the system are shown on Figures 5.17 to 5.27. Here, are presented the resulting probability distributions, showing the range that the given objective (TNPV, TGI or TCS) would fall between with 25% (red mid-band) and 95% (yellow mid-band) certainty.

Natural mortality wild stock

Variation in the instantaneous constant natural mortality rate of wild individuals in the population proved to be a highly critical factor, greatly influencing outputs. The range of variation of the TNPV was fairly wide, regardless of the management macro-scenario analysed and recruitment input in the system (Fig. 5.17).



TNPV, macro-scenario 1, Recruitment A

TNPV, macro-scenario 3, Recruitment A

TNPV, macro-scenario 1, Recruitment B

TNPV, macro-scenario 3, Recruitment B

Figure 5.17: Sensitivity of the TNPV for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the natural mortality rate of wild stock varying according to a normal distribution.

For remaining objectives (TGI and TCS) however, as recruitment level was higher, the range each objective would fall between was significantly wider (Fig. 4.18 and 4.19), showing the increasing influence of natural mortality of wild individuals as their stock builds up.

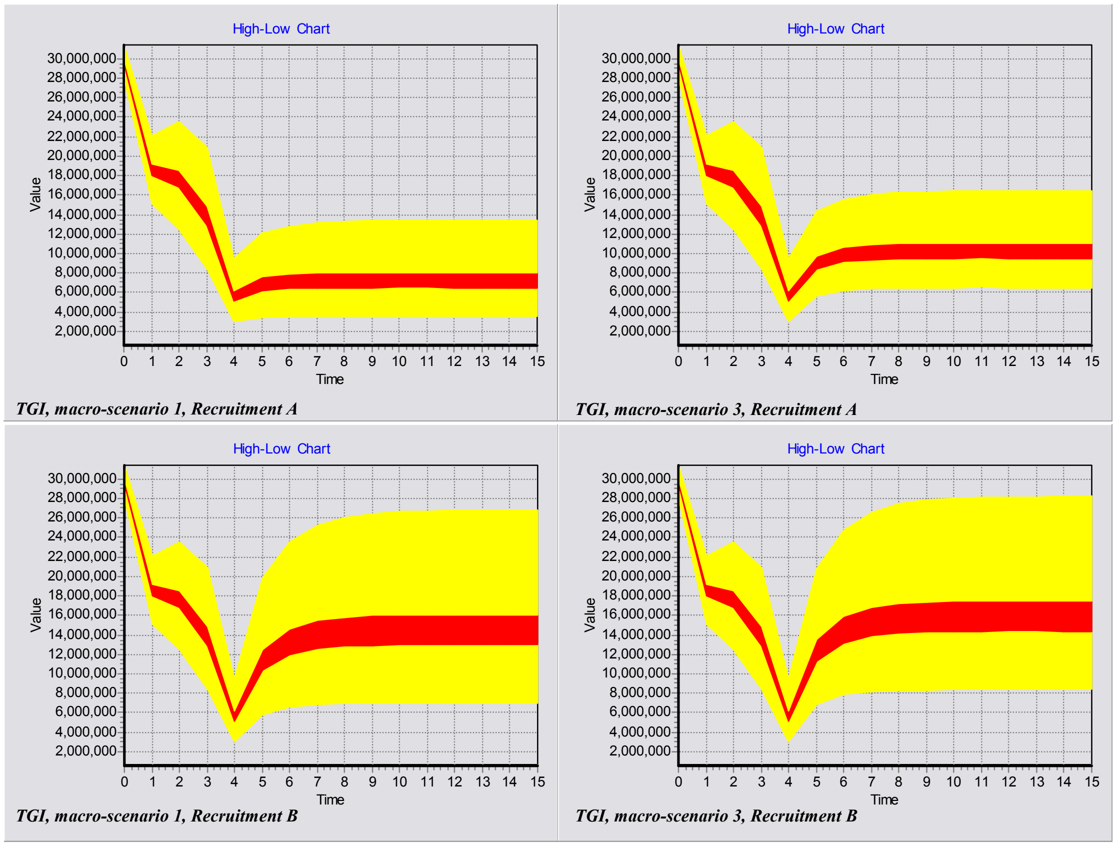


Figure 5.18: Sensitivity of the TGI for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the natural mortality rate of wild stock varying according to a normal distribution.

From this analysis, this parameter was confirmed to be an important agent of risk, and consequently acknowledged in the next stage of the study. Based on the sensitivity analysis outcomes the standard deviation used (M_W=0.132±0.066 year^{-1}), was considered to reflect a fairly sensible and safe boundary scenario for potential variation of this risk.

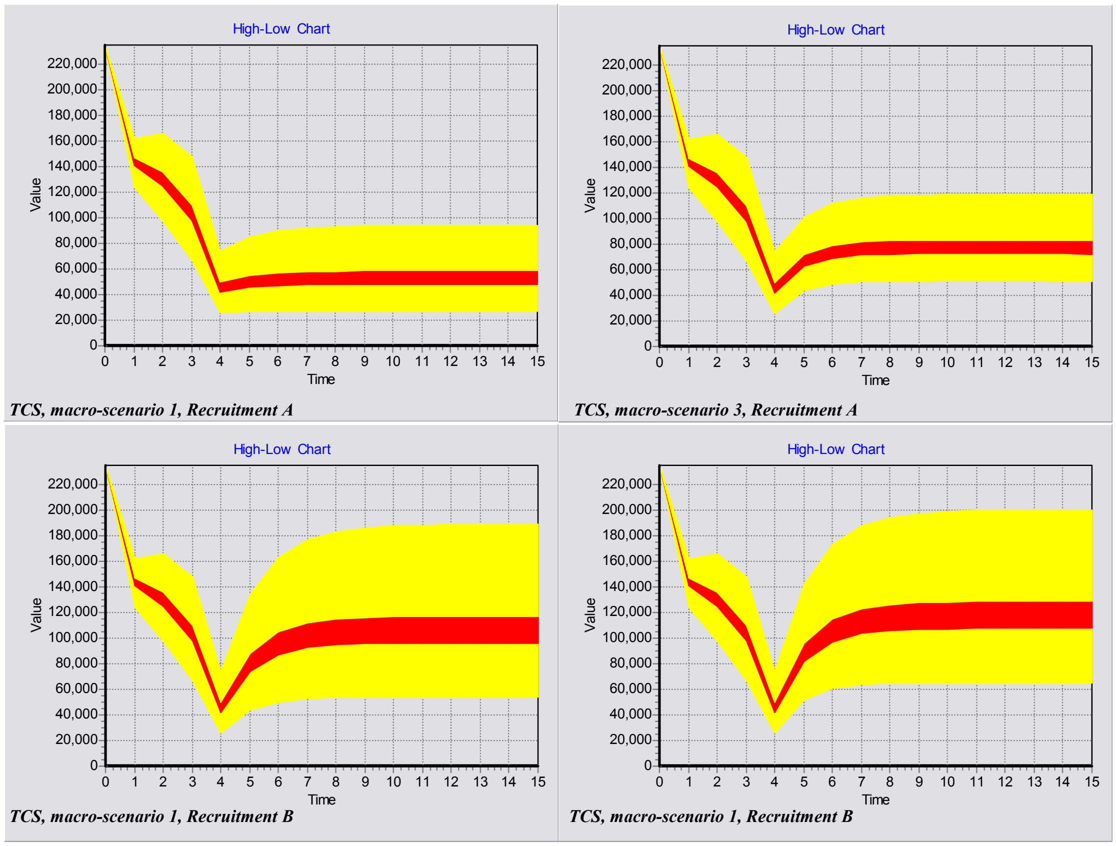


Figure 5.19: Sensitivity of the TCS for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the natural mortality rate of wild stock varying according to a normal distribution.

Natural mortality released stock

Independent of the recruitment level, the instantaneous constant natural mortality rate of the released individuals showed a comparatively low influence over major objectives (Fig. 5.20).

Being determined by the time the first batch of stocked juveniles enters the fishery, the influence of this factor starts on year 4, acting explicitly over the size of the stocks released. Even when restocking is large, because natural recruitment is limiting (recruitment level A), the overall size of the harvestable stock in the system ranges only between 55,000 and 85,000 individuals, not being badly influenced by natural mortality of stocked individuals.

From this analysis, this factor was not considered to be a highly determinant influencing risk factor in the 'manage risk' runs, keeping its original expected constant value estimated at 0.439 $year^{-1}$.

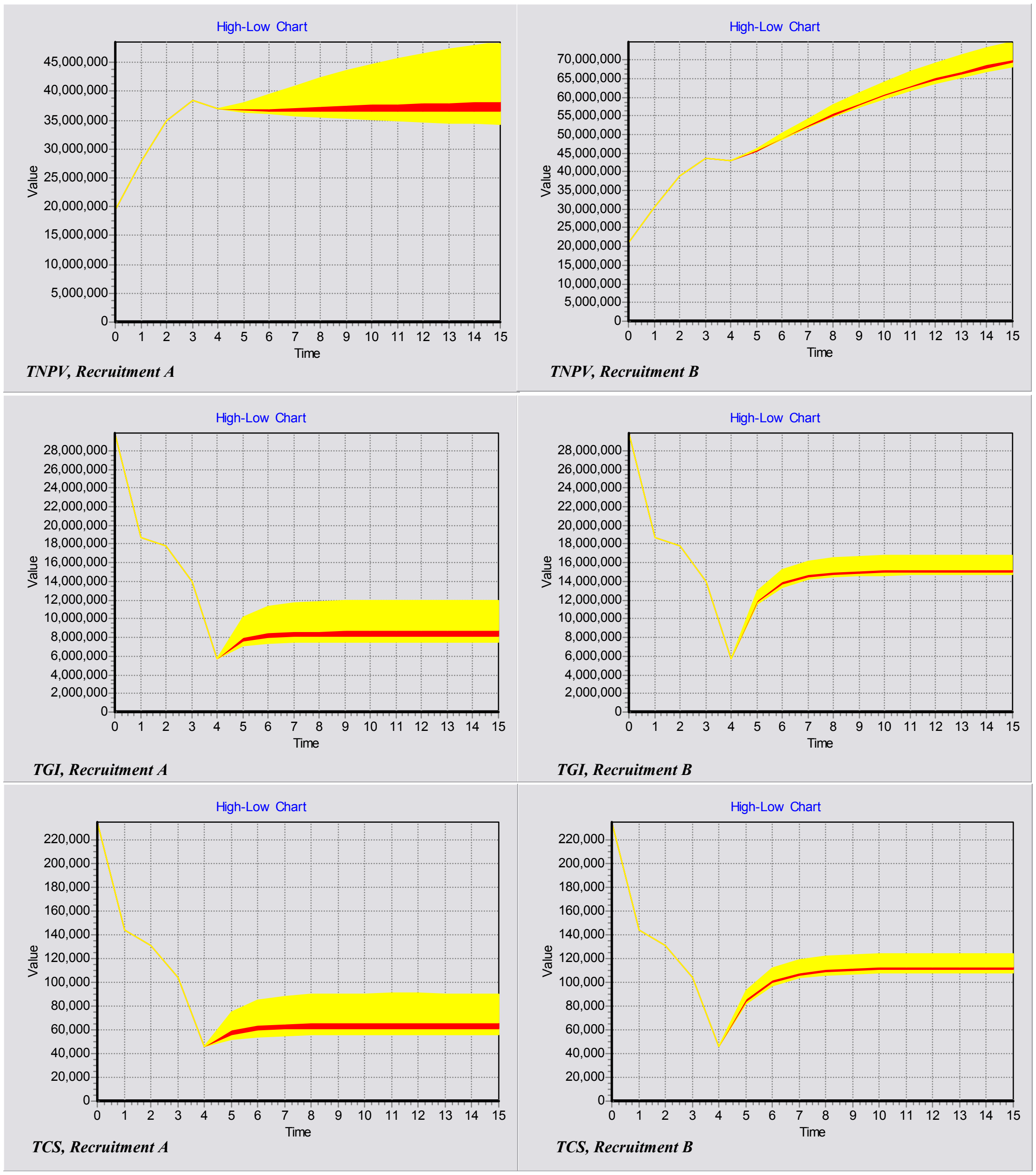


Figure 5.20: Sensitivity of the TNPV, TGI and TCS for macro-scenario 3 with two different recruitment levels analysed with respect to changes in the natural mortality rate of released stock varying according to a normal distribution.

Total natural recruitment

The three objectives were very sensitive to variation in total natural recruitment. This was even more significant for macro-scenario 1, in which the range the TNPV, TGI and TCS would fall between was wider than for macro-scenario 3 (Fig. 5.21). Excepting for TNPV of macro-scenario 3, the actual effect of this factor started on year 4, as is determined by the time required for the first batch of recruits to enter the fishery. In this particular case, this factor started influencing the overall economic performance from the very beginning, because the actual recruitment level will quantify the total seed released, and therefore restocking costs from year 0.

Based on these results, the total natural recruitment was verified to be a highly determinant risk factor. Its potential range of variation and associated uncertainty was taken into account for the final trials, on the basis of a uniform variation between 25,000 and 200,000 recruits per year for both macro-scenarios.

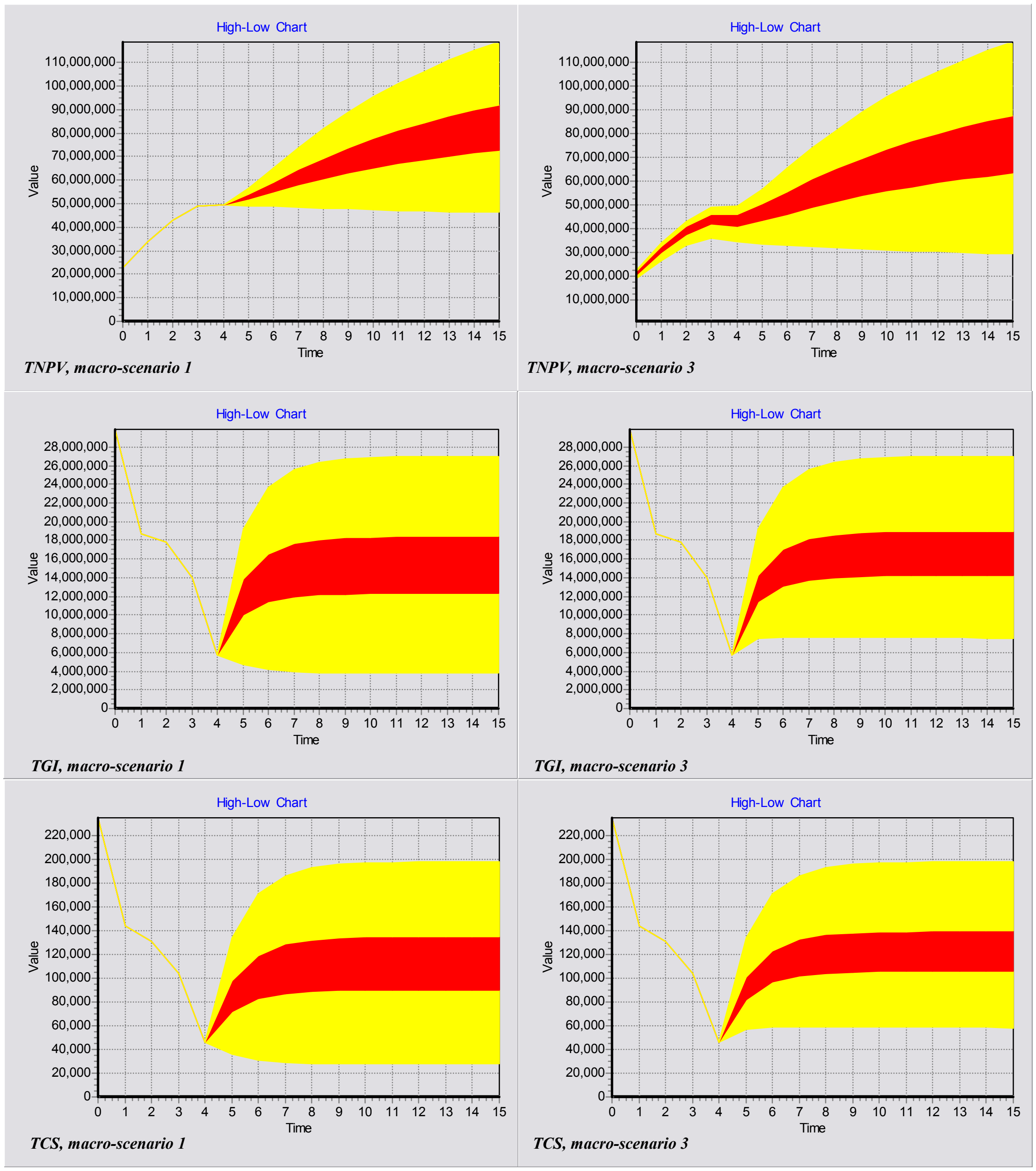


Figure 5.21: Sensitivity of the TNPV, TGI and TCS for macro-scenarios 1 and 3 analysed with respect to changes in the total natural recruitment varying according to a uniform distribution.

Catch rate

The average catch rate during fishing operations proved to be a highly critical factor, influencing to a large extent the economic performance of the project in both macro-scenarios and recruitment levels analysed (Fig. 5.22). The average catch rate determines the number of fishing sessions required to harvest the annual catch, and considering that harvesting costs were estimated as a function of the amount harvested in the fishery, the CPUE will ultimately determine the operating costs of fishing activities.

For that reason, this factor was highly acknowledged as a risk in the system, and further included on the basis of its average value and potential range of variation (665±279 urchins/fishing unit*day) in the 'manage risk' stage.

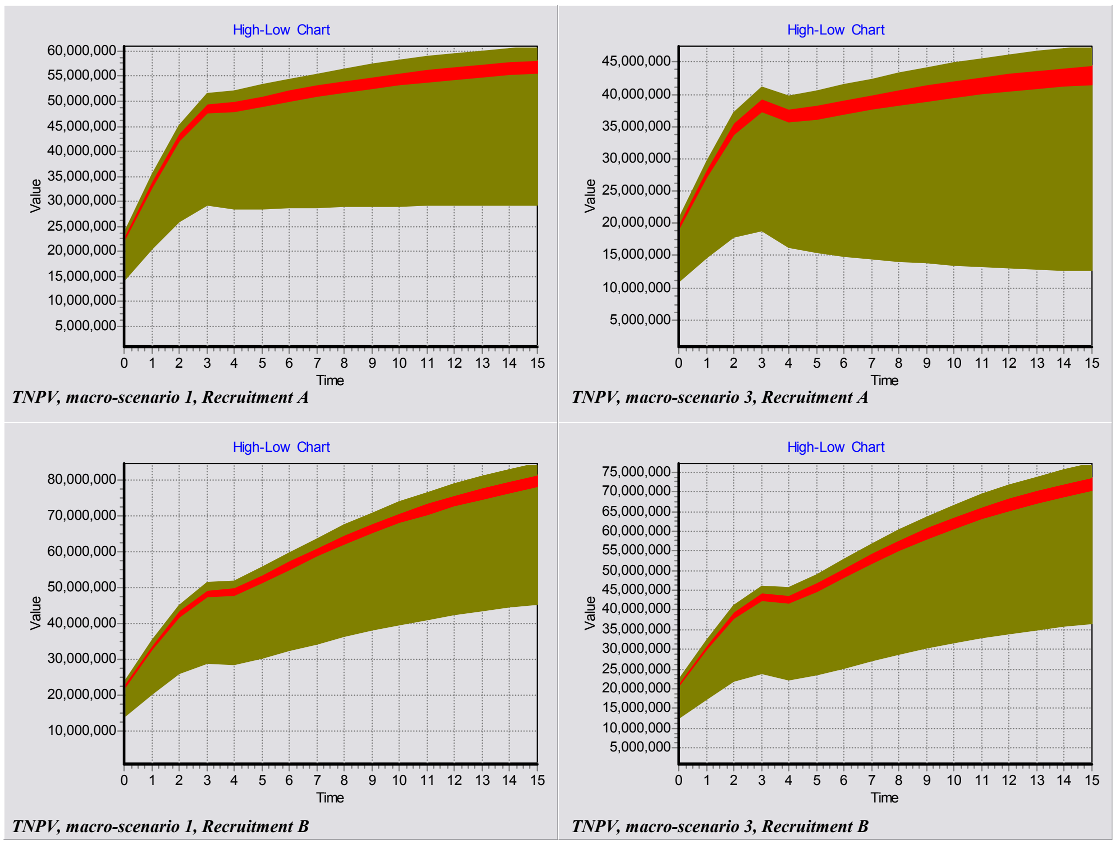


Figure 5.22: Sensitivity of the TNPV for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the catch rate varying according to a normal distribution.

Seed price

The unit price of the hatchery-reared juveniles for restocking was a highly critical factor, influencing the TNPV to a great extent (Fig. 5.23). The influence of this variable operating cost was evidently higher when restocking was larger, as determined by the lower recruitment levels (recruitment A) in the system.

This assumption was accounted as a major risk, thereafter associated with great deal of influence reflected in a uniformly distributed pattern of variability on time, with a minimum price of $0 and a maximum price of $50 per juvenile.

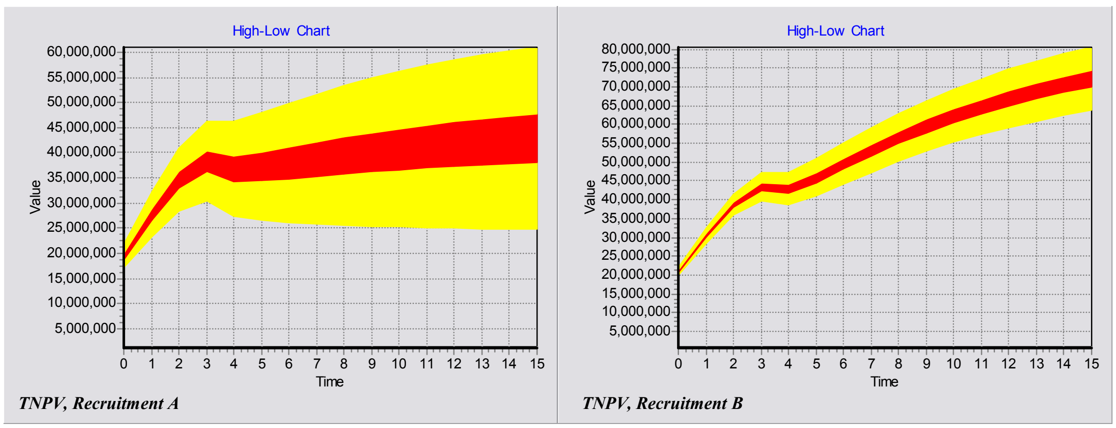


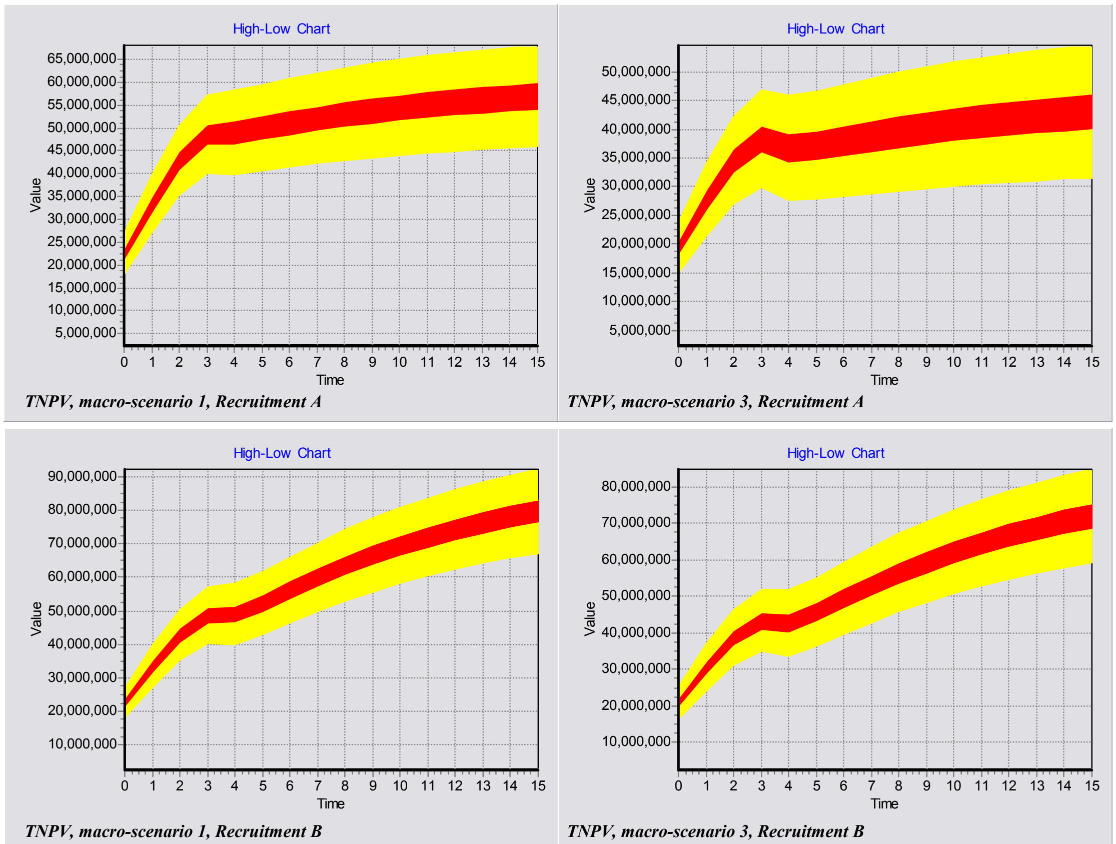
Figure 5.23: Sensitivity of the TNPV for macro-scenario 3 with two different recruitment levels, analysed with respect to changes in the unit seed price varying according to a uniform distribution.

Product market price

The TNPV proved to be moderately sensitive to changes in the price of product destined for both, national and international markets (Fig. 5.24 and 5.26).

With regards to the TGI, variation in product price for international markets resulted in a comparatively stronger response than for national markets (Fig. 5.25 and 5.27). In both cases however, the different levels of recruitment analysed did not make a significant impact on the outputs. This indicated the significance of this factor in the economic performance of the project regardless of the recruitment input in the system.

Based on these results and taking into account the typical dynamics of landed prices in Chile, often linked to a highly inconsistent and unpredictable patterns, these two critical assumptions were further included as uniform distributions in the 'manage risk' stage. Hence, the range of variation used was between $200 and $300 for national market, and $200 and $350 per unit for international markets destined product.



TNPV, macro-scenario 1, Recruitment A

TNPV, macro-scenario 3, Recruitment A

TNPV, macro-scenario 1, Recruitment B

TNPV, macro-scenario 3, Recruitment B

Figure 5.24: Sensitivity of the TNPV for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the unit product price for national markets varying according to a uniform distribution.

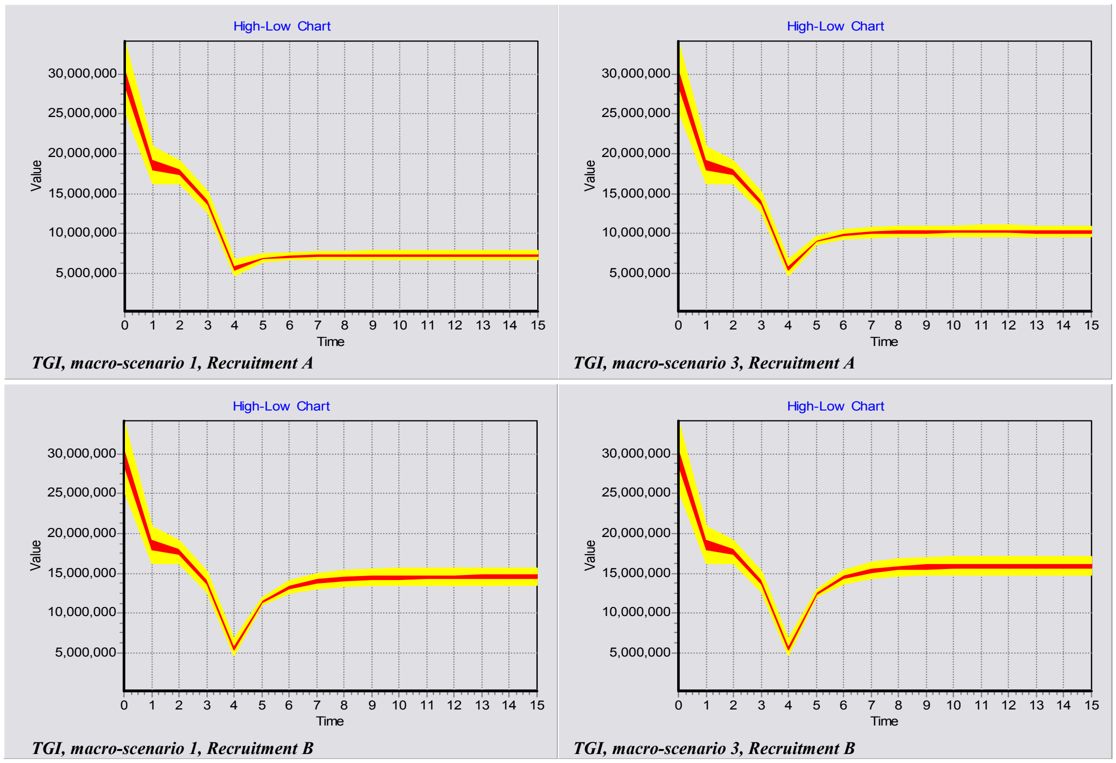


Figure 5.25: Sensitivity of the TGI for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the unit product price for national markets varying according to a uniform distribution.

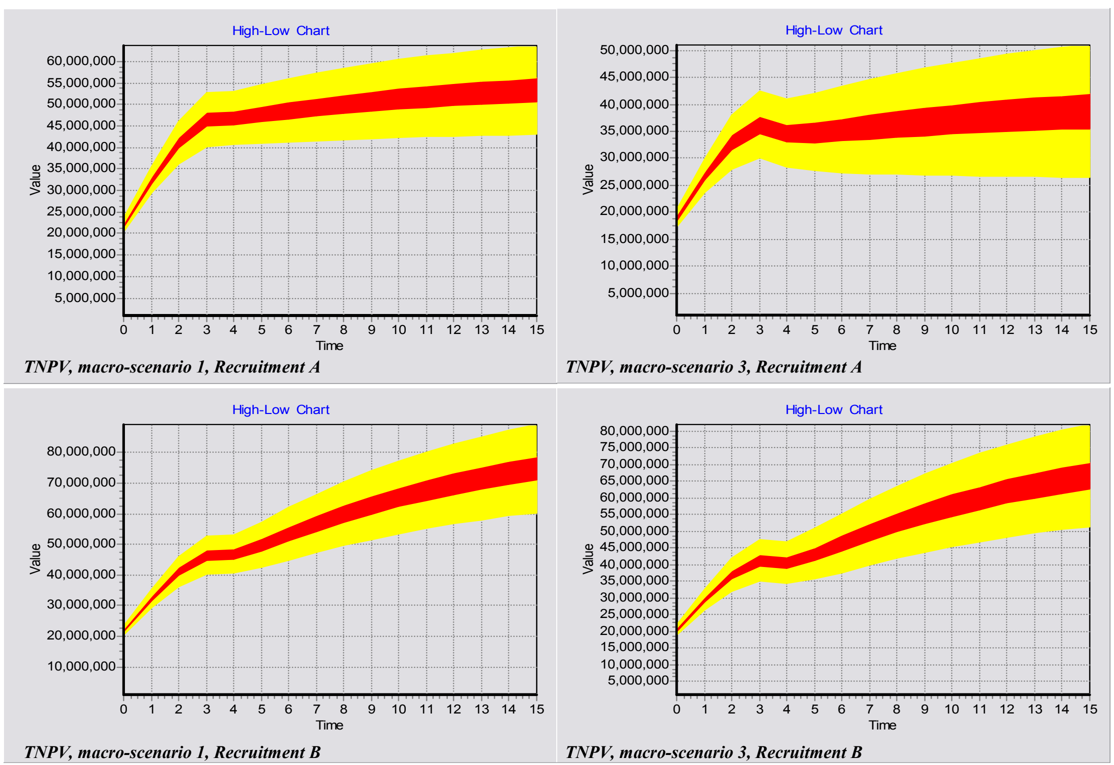


Figure 5.26: Sensitivity of the TNPV for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the unit product price for international markets varying according to a uniform distribution.

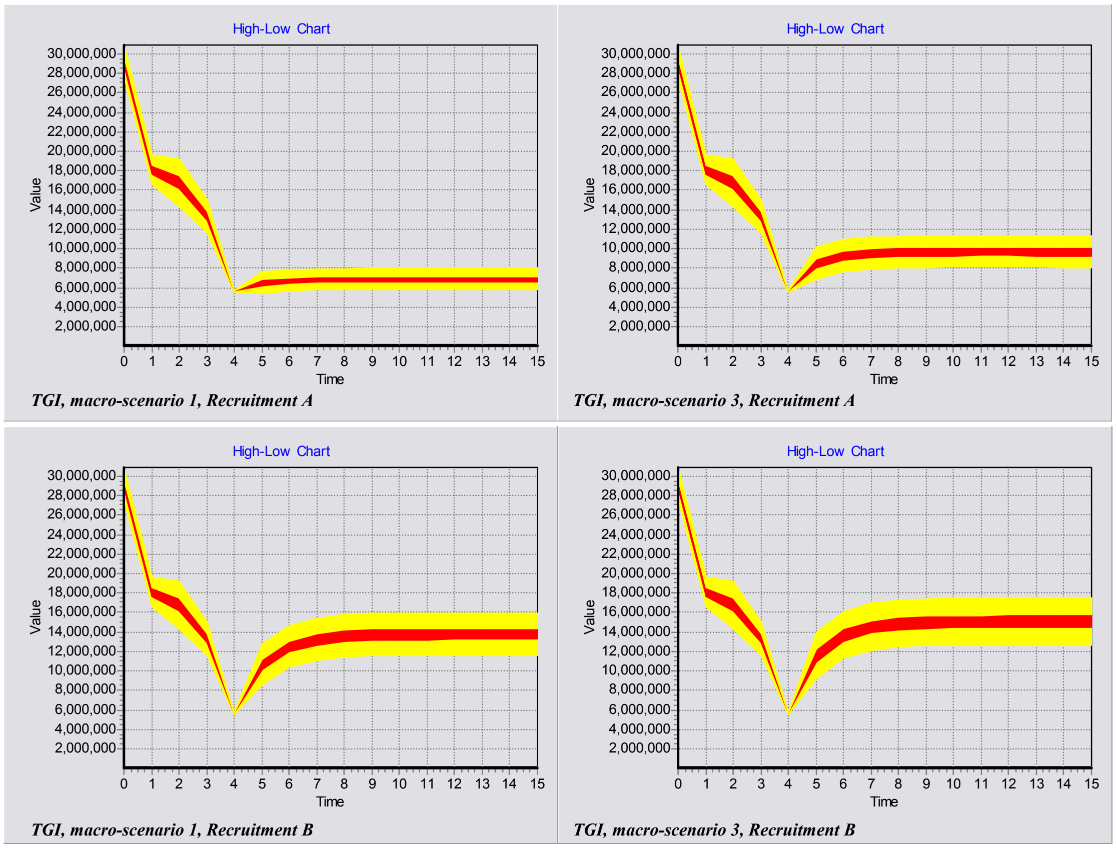


Figure 5.27: Sensitivity of the TGI for macro-scenarios 1 and 3 with two different recruitment levels analysed with respect to changes in the unit product price for international markets varying according to a uniform distribution.

5.4.3 STRATEGIC PLAN

Multi objective-based optimisation results are shown separately on Tables 5.11 to 5.15, which detail the final results for the optimisation target, and optimised decisions simulated for achieving the objectives set for macro-scenarios 1 and 3. Optimisation target results are expressed in terms of the level of confidence achieved using the set of decisions found. Here, are also included the objectives probability distributions resulting from each trade-off analysis, including the 25% and 90% certainty mid-bands (Fig. 5.28 to 5.32).

First round strategic plan

The outcomes of the preliminary multi-objective 'manage risk' approach were diverse in terms of, macro-scenarios, optimised decisions and target results (Table 5.11). Although the planning strategy was based on the use of equal weights of importance for the three major objectives, the best policies found could not achieve all the objectives targeted, favouring one or more to the detriment of others.

For macro-scenario 1, the TNPV and TCS targets were entirely achieved with the expected certainty, but the TGI returned minimum levels of confidence. Although not entirely satisfactory, multi-objective 'manage risk' results for macro-scenario 3 were better as the level of confidence for the TGI objective was higher than for macro-scenario 1, as a result of a similar fishing pressure, while keeping the TNPV and TCS within suitable certainty.

In addition, as shown on Fig. 5.28 macro-scenario 3 described a narrower distribution pattern, proving therefore to be a more robust management approach to variation on uncertain factors.

In both cases, the strategic plan generated involved realistic decision values, which although not producing optimum objective levels, in actual fact could be applied and improved.

Table 5.11: Summary of objectives, target results and optimised decisions obtained for the first round strategic planning towards the integrated achievement a positive total net present value, the expected total gross incomes and desired total commercial stock for macro-scenarios 1 and 3.

Result objectives	**$TNPV_{5}>0$ (11.11%)**	**$TNPV_{10}>0$ (11.11%)**	**$TNPV_{15}>0$ (11.11%)**	**Mean**
1:2:3=0.33:0.33:0.33	97.50%	92.50%	92.50%	**94.17%**
Macro-scenario 1	**$TGI_{5}>23*10^{6}$ (11.11%)**	**$TGI_{10}>23*10^{6}$ (11.11%)**	**$TGI_{15}>23*10^{6}$ (11.11%)**	
	5.00%	10.00%	12.50%	**9.17%**
	$TCS_{5}>150*10^{3}$ (11.11%)	**$TCS_{10}>150*10^{3}$ (11.11%)**	**$TCS_{15}>150*10^{3}$ (11.11%)**	**85.00%**
	85.00%	85.00%	85.00%	
Result objectives	**$TNPV_{5}>0$ (11.11%)**	**$TNPV_{10}>0$ (11.11%)**	**$TNPV_{15}>0$ (16.66%)**	**Mean**
1:2:3=0.33:0.33:0.33	92.50%	85.00%	85.00%	**87.50%**
Macro-scenario 3	**$TGI_{5}>23*10^{6}$ (11.11%)**	**$TGI_{10}>23*10^{6}$ (11.11%)**	**$TGI_{15}>23*10^{6}$ (11.11%)**	
	0.00%	15.00%	17.50%	**10.83%**
	$TCS_{5}>150*10^{3}$ (11.11%)	**$TCS_{10}>150*10^{3}$ (11.11%)**	**$TCS_{15}>150*10^{3}$ (11.11%)**	**88.33%**
	85.00%	90.00%	90.00%	

		Simulated result	
Decisions	**Macro-scenario**	**1**	**3**
AMEBR size (ha)		73.13	48.23
Fishing mortality (year^{-1})		0.408	0.471
Unitary fishing cost ($/day * fishing unit)		29,926	33,858
Fleet maintenance cost ($/ fishing unit * month)		9,817	13,028
Monitoring sessions (days/ year)		1	1
Required monitoring fleet (fishing units/ ha)		2	1
Unitary restocking labor cost ($/ labor unit * day)		-	10,152
Restocking events (days/ year)		-	8
Restocking rate (seeds/restocking labor unit)		-	5,034
Supporting fleet (fishing units)		-	4

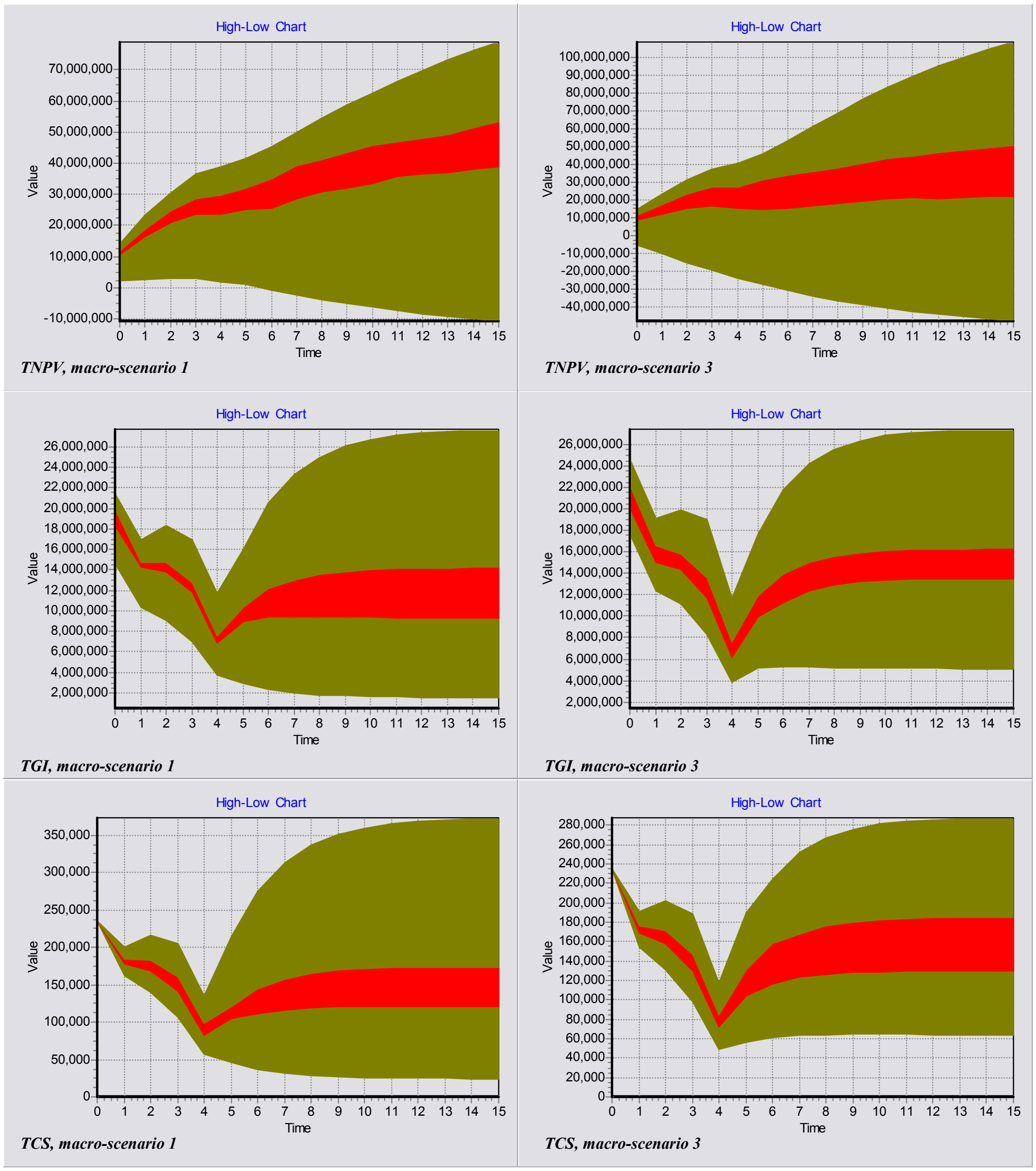


Figure 5.28: First output distribution for the TNPV, TGI and TCS for macro-scenarios 1 and 3 simulated using the preliminary set of decisions found while targeting the objective values at years 5, 10 and 15 with an 85% of confidence.

Second round strategic plan

As for the first multi-objective 'manage risk' approach; the results obtained at this stage also varied. The trade-off analysis, made it just possible to produce a better balance between the major objectives set for macro-scenario 1, while for macro-scenario 3 the level of confidence for the objectives was unaffected (Table 5.12).

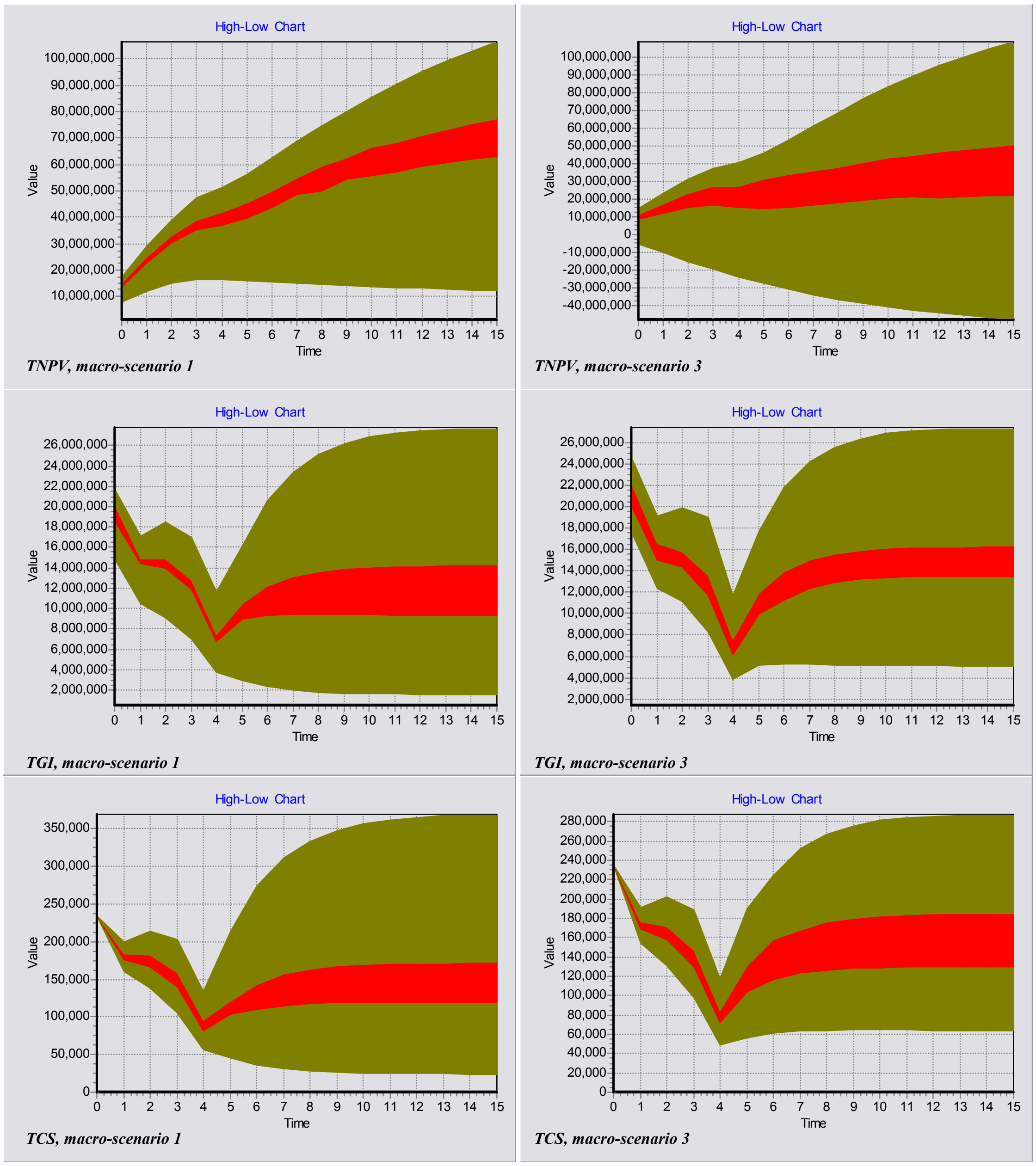
For macro-scenario 1 though the objective levels TCS were lower in comparison to the first multi-objective 'manage risk' approach; objective levels for the TGI were slightly improved, getting closer to the level obtained for macro-scenario 3. In both cases, though the target for the TGI still remained distant, returning only about an 11% in the best case.

Yet again, as shown on Fig. 5.29, considering this new and improved output plan for macro-scenario 1, macro-scenario 3 still remained a more robust management option.

Table 5.12: Summary of objectives, target results and optimised decisions obtained for the second round strategic planning towards the integrated achievement a positive total net present value, the expected total gross incomes and desired total commercial stock for macro-scenarios 1 and 3.

Result objectives 1:2:3=0.50:0.33:0.16 Macro-scenario 1	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	97.50%	92.50%	92.50%	**94.17%**
	TGI_5>23*10^6 (11.11%)	**TGI_{10}>23*10^6 (11.11%)**	**TGI_{15}>23*10^6 (11.11%)**	
	5.00%	12.50%	12.50%	**10.00%**
	TCS_5>150*10^3 (5.33%)	**TCS_{10}>150*10^3 (5.33%)**	**TCS_{15}>150*10^3 (5.33%)**	
	80.00%	85.00%	85.00%	**83.33%**
Result objectives 1:2:3=0.50:0.33:0.16 Macro-scenario 3	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	92.50%	85.00%	85.00%	**87.50%**
	TGI_5>23*10^6 (11.11%)	**TGI_{10}>23*10^6 (11.11%)**	**TGI_{15}>23*10^6 (11.11%)**	
	0.00%	15.00%	17.50%	**10.83%**
	TCS_5>150*10^3 (5.33%)	**TCS_{10}>150*10^3 (5.33%)**	**TCS_{15}>150*10^3 (5.33%)**	
	85.00%	90.00%	90.00%	**88.33%**

		Simulated result	
Decisions	**Macro-scenario**	**1**	**3**
AMEBR size (ha)		33.43	48.23
Fishing mortality ($year^{-1}$)		0.414	0.471
Unitary fishing cost ($/day * fishing unit)		22,039	33,858
Fleet maintenance cost ($/ fishing unit * month)		10,836	13,028
Monitoring sessions (days/ year)		2	1
Required monitoring fleet (fishing units/ ha)		1	1
Unitary restocking labor cost ($/ labor unit * day)		-	10,152
Restocking events (days/ year)		-	8
Restocking rate (seeds/restocking labor unit)		-	5,034
Supporting fleet (fishing units)		-	4



TNPV, macro-scenario 1

TNPV, macro-scenario 3

TGI, macro-scenario 1

TGI, macro-scenario 3

TCS, macro-scenario 1

TCS, macro-scenario 3

Figure 5.29: Second output distribution for TNPV, TGI, and TCS for macro-scenarios 1 and 3 simulated using the second best set of decisions found while targeting the objective values at years 5, 10 and 15 with an 85% of confidence.

Third round strategic plan

Although the third strategic planning approach was aimed at improving the results of the previous round, outputs of this analysis were not greatly constructive. For macro-scenario 1 although the TNPV and TCS output levels of certainty were slightly improved, the corresponding levels of the TGI were maintained, and the resulting best set of decisions found for macro-scenario 3 was again identical to those returned on the first run (Table 5.13).

Table 5.13: Summary of objectives, target results and optimised decisions obtained for the third round strategic planning towards the integrated achievement a positive total net present value, the expected total gross incomes and desired total commercial stock for macro-scenarios 1 and 3.

Result objectives 1:2:3=0.50:0.375:0.125 Macro-scenario 1	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	97.50%	97.50%	95.00%	**96.67%**
	$TGI_5>23*10^6$ (12.50%)	**$TGI_{10}>23*10^6$ (12.50%)**	**$TGI_{15}>23*10^6$ (12.50%)**	
	5.00%	12.50%	12.50%	**10.00%**
	$TCS_5>150*10^3$ (4.16%)	**$TCS_{10}>150*10^3$ (4.16%)**	**$TCS_{15}>150*10^3$ (4.16%)**	**84.17%**
	82.50%	85.00%	85.00%	
Result objectives 1:2:3=0.50:0.375:0.125 Macro-scenario 3	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	92.50%	85.00%	85.00%	**87.50%**
	$TGI_5>23*10^6$ (12.50%)	**$TGI_{10}>23*10^6$ (12.50%)**	**$TGI_{15}>23*10^6$ (12.50%)**	
	0.00%	15.00%	17.50%	**10.83%**
	$TCS_5>150*10^3$ (4.16%)	**$TCS_{10}>150*10^3$ (4.16%)**	**$TCS_{15}>150*10^3$ (4.16%)**	**88.33%**
	85.00%	90.00%	90.00%	

		Simulated result	
Decisions	**Macro-scenario**	**1**	**3**
AMEBR size (ha)		42.14	48.23
Fishing mortality ($year^{-1}$)		0.415	0.471
Unitary fishing cost ($/day * fishing unit)		11,809	33,858
Fleet maintenance cost ($/ fishing unit * month)		13,282	13,028
Monitoring sessions (days/ year)		4	1
Required monitoring fleet (fishing units/ ha)		1	1
Unitary restocking labor cost ($/ labor unit * day)		-	10,152
Restocking events (days/ year)		-	8
Restocking rate (seeds/restocking labor unit)		-	5,034
Supporting fleet (fishing units)		-	4

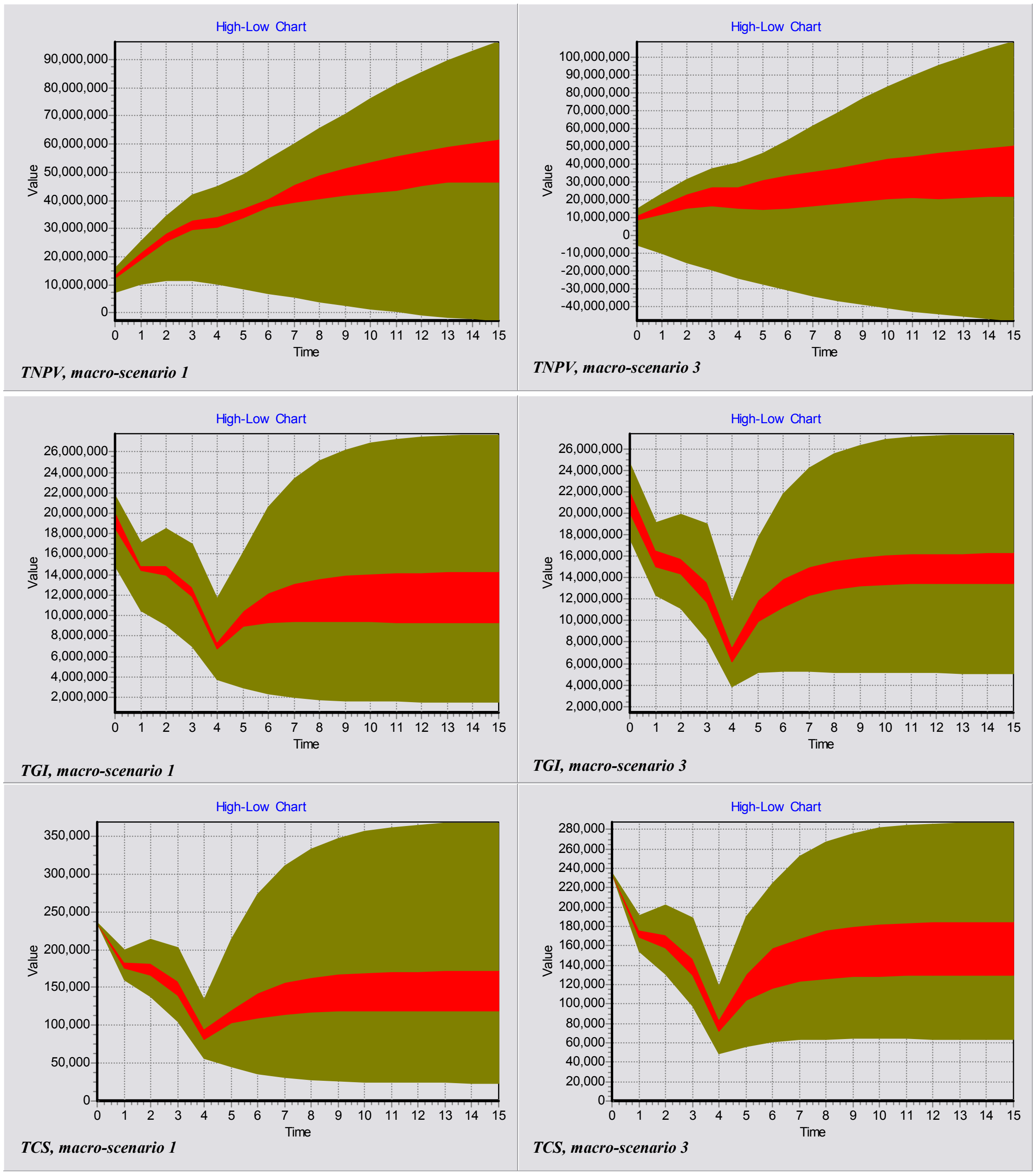


Figure 5.30: Third output distribution for TNPV, TGI, and TCS for macro-scenarios 1 and 3 simulated using the best set of decisions found while targeting the objective values at years 5, 10 and 15 with an 85% of confidence.

Fourth round strategic plan

The outputs of this analysis were moderately productive, improving to some extent the results of the previous rounds. Thus, the trade-off analysis made it possible to produce a much better balance between the major objectives set for macro-scenario 3, while for macro-scenario 1 the level of confidence for the objectives was unaffected (Table 5.14).

For macro-scenario 3 the TNPV output levels of certainty were slightly improved. The corresponding levels of the TCS and TGI were better balanced, doubling-up the level in the latter, while keeping an acceptable level in the former. This management plan however, considers over twice the fishing pressure of the previous plan found (0.47 year^{-1}). As a result, the harvestable stock drops off, but corresponding incomes from the fishery are proportionally increased.

Describing a fairly narrower distribution patter, this new and much more improved management plan designed for macro-scenario 3, proved to be significantly more robust to uncertainty than macro-scenario 1 (Fig. 5.31).

Table 5.14: Summary of objectives, target results and optimised decisions obtained for the third round strategic planning towards the integrated achievement a positive total net present value, the expected total gross incomes and desired total commercial stock for macro-scenarios 1 and 3.

Result objectives 1:2:3=0.50:0.40:0.10 Macro-scenario 1	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	97.50%	97.50%	97.50%	**97.50%**
	TGI_5>23*10^6 (13.33%)	**TGI_{10}>23*10^6 (13.33%)**	**TGI_{15}>23*10^6 (13.33%)**	
	5.00%	12.50%	12.50%	**10.00%**
	TCS_5>150*10^3 (3.33%)	**TCS_{10}>150*10^3 (3.33%)**	**TCS_{15}>150*10^3 (3.33%)**	
	82.50%	85.00%	85.00%	**84.17%**
Result objectives 1:2:3=0.50:0.40:0.10 Macro-scenario 3	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	97.50%	97.50%	95.00%	**96.67%**
	TGI_5>23*10^6 (13.33%)	**TGI_{10}>23*10^6 (13.33%)**	**TGI_{15}>23*10^6 (13.33%)**	
	7.50%	25.00%	25.50%	**19.17%**
	TCS_5>150*10^3 (3.33%)	**TCS_{10}>150*10^3 (3.33%)**	**TCS_{15}>150*10^3 (3.33%)**	
	52.50%	67.50%	67.50%	**62.50%**

		Simulated result	
Decisions	**Macro-scenario**	**1**	**3**
AMEBR size (ha)		42.05	62.22
Fishing mortality (year^{-1})		0.415	1.030
Unitary fishing cost ($/day * fishing unit)		16,129	15,551
Fleet maintenance cost ($/ fishing unit * month)		10,104	14,643
Monitoring sessions (days/ year)		3	3
Required monitoring fleet (fishing units/ ha)		1	1
Unitary restocking labor cost ($/ labor unit * day)		-	11,033
Restocking events (days/ year)		-	6
Restocking rate (seeds/restocking labor unit)		-	4,724
Supporting fleet (fishing units)		-	1

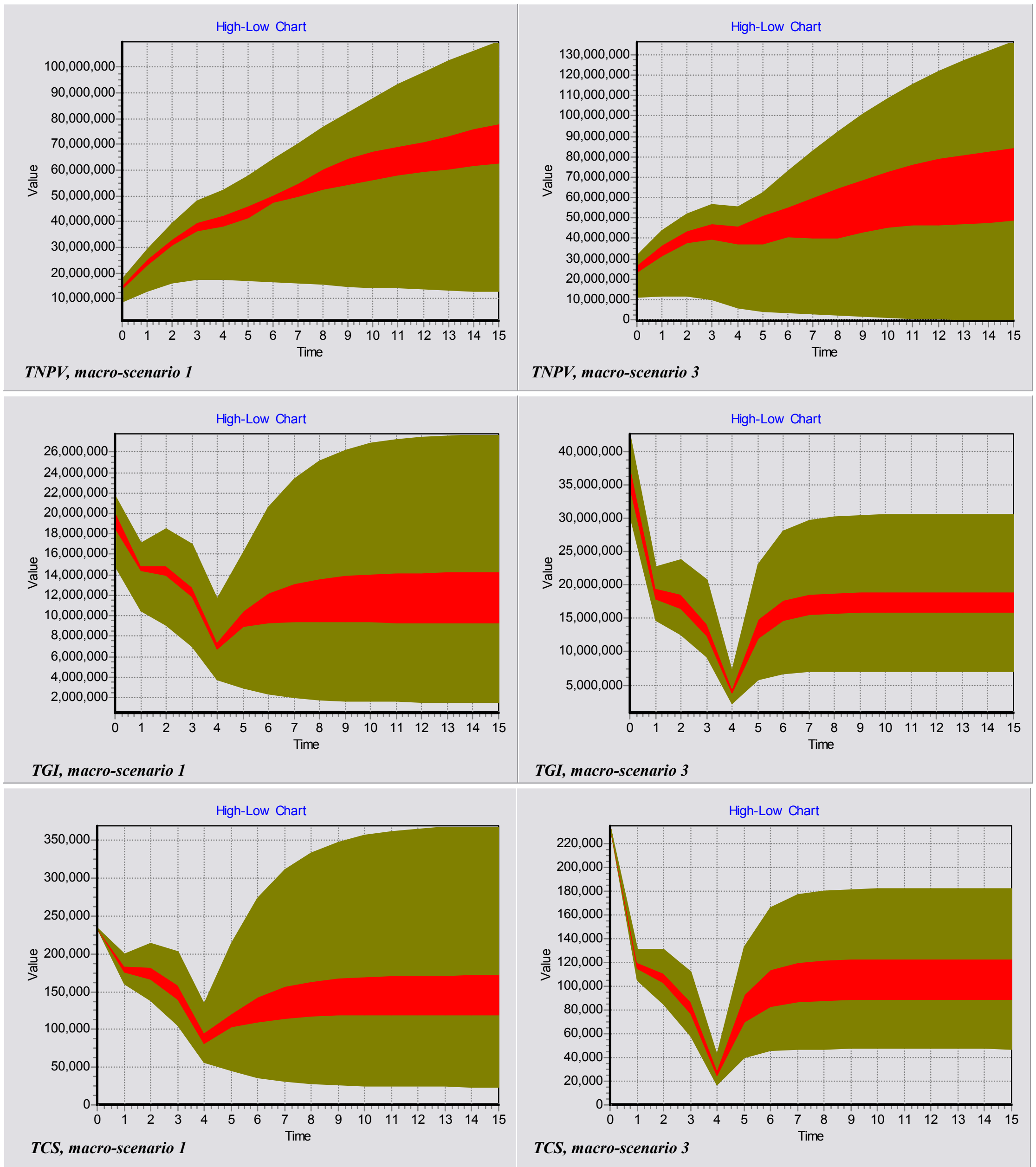


Figure 5.31: Fourth output distribution for TNPV, TGI, and TCS for macro-scenarios 1 and 3 simulated using the best set of decisions found while targeting the objective values at years 5, 10 and 15 with an 85% of confidence.

Fifth round strategic plan

Ultimately, the trade-off analysis carried in the final round strategic 'manage risk' made it just possible to produce a better balance between the major objectives set for macro-scenario 1, whereas for macro-scenario 3 the level of confidence previously obtained for the objectives remained the same (Table 5.15).

For macro-scenario 1 though the objective levels TCS were lower in comparison to the fourth round; objective levels for the TGI were improved in five points. As for macro-scenario 3, this situation was a result of high fishing intensity, which diminished the commercial stock in twenty percent on average over the evaluation points.

Once more, as illustrated on Fig. 5.34, considering this new and improved output plan for macro-scenario 1, macro-scenario 3 still proved more robust to uncertainty. In addition, excepting for the TCS at year 5, this alternative returned higher levels of confidence for all of the targets.

Table 5.15: Summary of objectives, target results and optimised decisions obtained for the final round strategic planning towards the integrated achievement a positive total net present value, the expected total gross incomes and desired total commercial stock for macro-scenarios 1 and 3.

Result objectives 1:2:3=0.50:0.45:0.05 Macro-scenario 1	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	90.00%	90.00%	90.00%	**90.00%**
	TGI_5>23*10^6 (15.00%)	**TGI_{10}>23*10^6 (15.00%)**	**TGI_{15}>23*10^6 (15.00%)**	
	5.00%	20.00%	20.00%	**15.00%**
	TCS_5>150*10^3 (1.66%)	**TCS_{10}>150*10^3 (1.66%)**	**TCS_{15}>150*10^3 (1.66%)**	
	82.50%	55.00%	55.00%	**64.17%**
Result objectives 1:2:3=0.50:0.45:0.05 Macro-scenario 3	**$TNPV_5$>0 (16.66%)**	**$TNPV_{10}$>0 (16.66%)**	**$TNPV_{15}$>0 (16.66%)**	**Mean**
	95.00%	95.00%	95.00%	**95.00%**
	TGI_5>23*10^6 (15.00%)	**TGI_{10}>23*10^6 (15.00%)**	**TGI_{15}>23*10^6 (15.00%)**	
	7.50%	25.00%	25.50%	**19.17%**
	TCS_5>150*10^3 (1.66%)	**TCS_{10}>150*10^3 (1.66%)**	**TCS_{15}>150*10^3 (1.66%)**	
	52.50%	67.50%	67.50%	**62.50%**

		Simulated result	
Decisions	**Macro-scenario**	**1**	**3**
AMEBR size (ha)		57.08	49.28
Fishing mortality ($year^{-1}$)		1.039	1.028
Unitary fishing cost ($/day * fishing unit)		25,704	25,228
Fleet maintenance cost ($/ fishing unit * month)		13,665	30,034
Monitoring sessions (days/ year)		3	1
Required monitoring fleet (fishing units/ ha)		3	1
Unitary restocking labor cost ($/ labor unit * day)		-	11,770
Restocking events (days/ year)		-	8
Restocking rate (seeds/restocking labor unit)		-	4,130
Supporting fleet (fishing units)		-	2

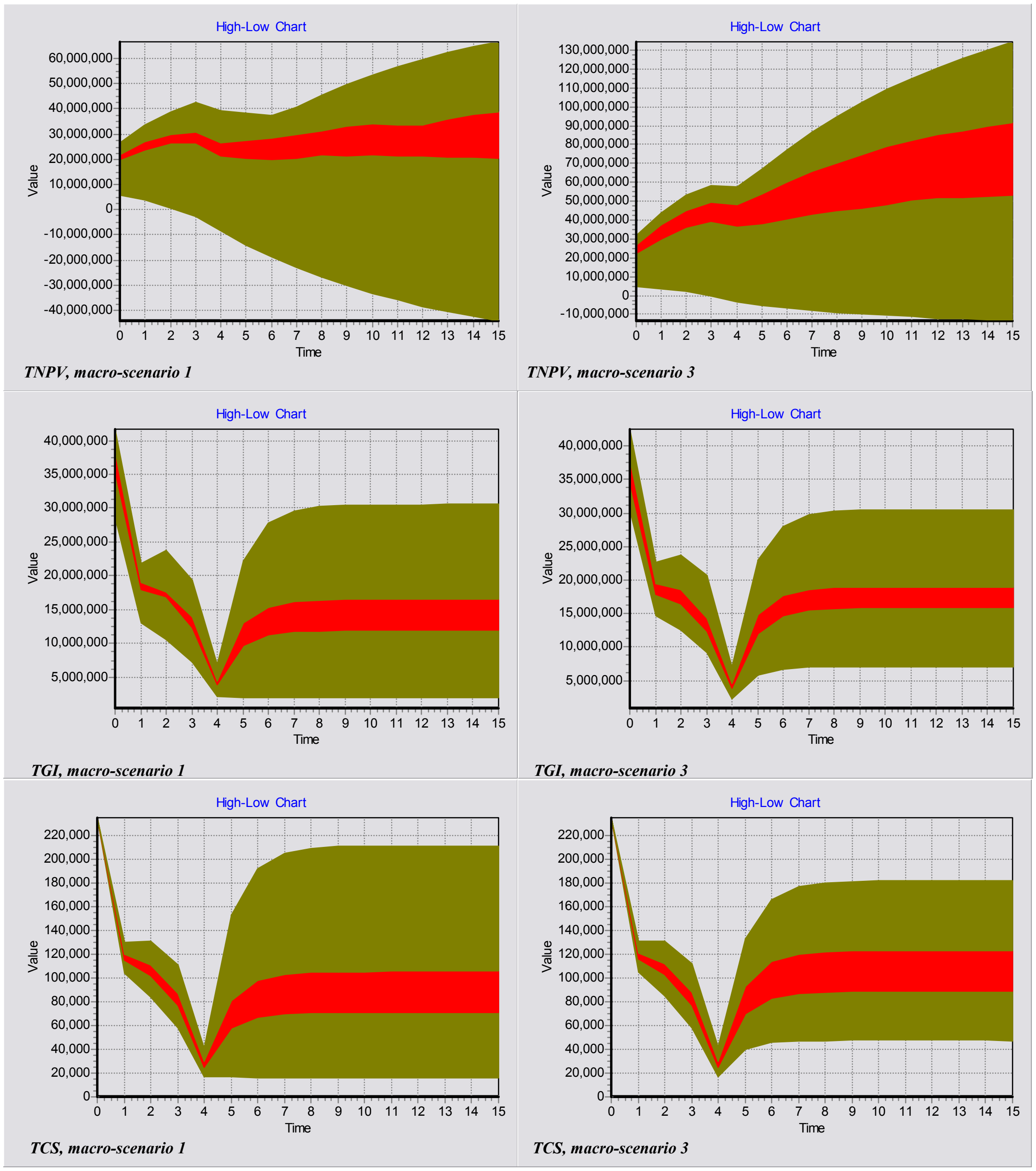


Figure 5.32: Fourth output distribution for TNPV, TGI, and TCS for macro-scenarios 1 and 3 simulated using the best set of decisions found while targeting the objective values at years 5, 10 and 15 with an 85% of confidence.

5.5 DISCUSSION

As a fundamental building block of the bio-socio-economic modelling process, the final stage of this research focused on a real case study-based run, formal implementation, and practical assessment of the BSESM in the actual fishery system. The goals of this stage were to design, run, and sensitise various management approaches, and ultimately develop a long-term management plan for the red sea urchin fishery in Quintay Bay. The final part of this work also aimed to assess the use of the software as a tool to support decision-making for the management of the target species within the AMEBR system.

The first steps comprised the static and dynamic testing of the simulation model's structure and operation, the case study input parameters data process and entry, and the design and deterministic run of three different management macro-scenarios. Secondly, having analysed the case study outputs, two macro-scenarios were explicitly selected. Next, as the assumptions used in the model run were potentially associated with high variability and uncertainty, a sensitivity analysis was carried out to analyse their influence and the effects of their changes on the major biological and economic objectives of the system: total commercial stock (TCS) of the population, total gross incomes (TGI) generated from the fishery, and the total net present value (TNPV) of the project. As critical assumptions (risks) in the model were verified, and their effect on system objectives assessed, the final step was the risk management analysis for strategic planning. The ultimate approach to manage risk was based on the search for specific decision values forming up the policy (strategic management plan) that fulfilled and balanced the trade-offs between biological and economic objectives with a suitable level of confidence, showing therefore a sufficient robustness to changes on critical assumptions. The final step consisted of field-based work with the local fishing association representatives, technical support unit members, and staff of the Marine Research Centre of Quintay, at which the global practical application of the BSESM was assessed. Through discussion groups, interviews, tutorials and various presentations carried out on a number of meetings at Quintay, the model was implemented, to evaluate its usefulness and its future applications.

The final outputs of the process were two alternative strategic plans for long-term management of the red sea urchin fishery at the AMEBRQ. These alternatives consisted of the best set of decisions (policy) to be implemented to achieve the stated objectives with the maximum level of confidence, taking into account the potential variability of the major risks, considered to apply under the two different macro-management regimes.

The first option proposed (Table 5.16) was the best policy found, for use with the traditional approach (macro-scenario 1). Under this approach restocking is not considered, and management is only regulated by the minimum legal size and seasonal restriction for capture.

Table 5.16: Strategic plan for long-term management of the red sea urchin fishery under a traditional size/season restriction-based regime in the AMEBRQ.

Decisions	Optimum value
AMEBR size (ha)	57.08
Fishing mortality (year^{-1})	1.039
Unitary fishing cost ($/day * fishing unit)	25,704
Fleet maintenance cost ($/ fishing unit * month)	13,665
Monitoring sessions (days/ year)	3
Required monitoring fleet (fishing units/ ha)	3

As a result of applying this policy, the average predicted level of achievement for the system targets, were of: 90% for a positive TNPV of the project, 15% for the TGI to be larger than 23 million pesos, 64% for the TCS to be larger than 85,000 individuals (see Table 5.15 for details).

The second option (Table 5.17) was the optimum policy, in which a flexible and adaptive integrated restocking and exploitation programme (macro-scenario 3) is considered. Here, restocking and/or exploitation may be applied and mixed over time, varying in intensity and pattern depending on the state of the stocks and recruitment level.

Table 5.17: Strategic plan for long-term management of the red sea urchin fishery under an integrated adaptive restocking and exploitation-based regime in the AMEBRQ.

Decisions	Optimum value
AMEBR size (ha)	49.28
Fishing mortality (year^{-1})	1.028
Unitary fishing cost ($/day * fishing unit)	25,228
Fleet maintenance cost ($/ fishing unit * month)	30,034
Monitoring sessions (days/ year)	1
Required monitoring fleet (fishing units/ ha)	1
Unitary restocking labor cost ($/ labor unit * day)	11,770
Restocking events (days/ year)	8
Restocking rate (seeds/restocking labor unit)	4,130
Supporting fleet (fishing units)	2

If this policy is applied, the average predicted confidence levels of achievement for the system targets, were of: 95.00% for a positive TNPV of the project, 19% for the TGI to be larger than 23 million pesos, and 63% for the TCS to be larger than 85,000 individuals (see table 5.15 for details).

The case study-based run outputs showed that macro-scenario 3 was the best management alternative in terms of biological effects on stocks and incomes from their exploitation. In contrast, macro-scenario 2 returned fairly poor results and projections for stocks dynamics and economic returns. Also not entirely satisfactory, corresponding outputs for macro-scenario 1 were slightly better than those obtained for macro-scenario 2, but worse than those generated from macro-scenario 3.

Although returning better population levels and related incomes, it was found that restocking is not economically feasible, basically because the costs of stocking would exceed the revenue from harvesting stocked urchins. Accordingly, the overall economic performance of macro-scenario 3 was consistently lower than macro-scenario 1, and returned a positive TNPV simply because wild stocks offset much of the loss. However, restocking still demonstrated to be beneficial, in terms of the total incomes, commercial stock, but more importantly to support a system with highly variable and limiting recruitment levels.

Despite their effectiveness in determining the projections for each approach, these results have to be analysed in the perspective of the current management approaches for the red sea urchin in Chile.

Here the most widely and traditionally applied management regime (macro-scenario 1) did not prove to be satisfactory. Under limiting recruitment conditions, this management described the characteristic pattern of overexploitation, resulting on a strong impact and eventual depletion of natural stocks. When considering the optimistic scenario of constant and not limiting recruitment levels, this option returned improved outputs for both the total population and stock, which however did not achieve the targets.

This exploitation and management model has unquestionably been responsible for the current state of most important red sea urchin natural stocks along the Chilean coastline, which are heavily diminished, rapidly declining or simply in complete state of overexploitation (Gutierrez and Otsu, 1975; Bay-Schimidt, 1977; Deppe and Viviani, 1977; San Martin, 1987; Castilla, 1988; Castilla, 1990; Oliva and Garrido, 1994; Paredes, 1988; Stotz *et al.*, 1992; Gonzalez, 1996; Castilla, 1997; Barahona and Jerez, 1998).

As natural recruitment is highly variable and limited, population dynamics resulting from this management also illustrated the typical evolution of a sea urchin or other commercial benthic resource in a Chilean cove, where natural stocks are heavily exploited at commercial levels until they reach a sub optimum state of equilibrium, not been able to recover naturally.

Bearing in mind that fishery managers must never take their decisions based on optimistic scenarios (e.g. high and constant recruitment levels), these results demonstrated that even within the system of AMEBR, the sole application of traditional fishing regulations currently used for this species, are not sufficient to stop this trend and to recover the fishery. Accordingly, further administration measures and a wider strategic approach, considering alternative management options is highly necessary.

In this context, the outcomes from the third management option provided a more positive picture that in spite of not completely meeting objectives was the best alternative in population levels and dynamics. In particular when recruitment is restraining (recruitment level A), an integrated restocking and exploitation programme may be the way to tackle the limiting factor of the fishery. The stocking-based strategy proposed will enhance and recover natural stocks by supporting natural recruitment with controlled release of hatchery-reared juveniles, allowing at the same time a flexible capture strategy to sustain the fishing community that relies on this resource.

Nevertheless the economic analysis showed stocking to be economically unfeasible, being the instantaneous natural mortality of released individuals (M_R) and the unit cost of the seed the major influencing factors into the economic viability of this option. Running a single-variable optimisation analysis (Tables A.15 and A.16, Appendix 4) it was found that natural mortality would have to be improved from 0.439 year^{-1} to 0.142 year^{-1} or the average unit cost of restocking material reduced from \$25 to \$17, to make stocking viable. Under these settings, either a higher survival rate would be needed to generate sufficient incomes to cover major restocking costs and return a positive payment, or a cost reduction would be essential to make up for the loss due to high natural mortality rates on released urchins as compared to wild individuals.

Although outputs for macro-scenario 2 were comparatively poor in terms of major objectives, these should be analysed as they directly link to the current management system in the study area. These showed that the original integrated restocking and management programme (del Campo and Perez, 1999) ought to be modified and turned into a more flexible and adaptive approach to achieve expected long-term outcomes. This analysis may be used to validate projections and introduce prospective amendments using outputs for macro-scenario 3, to propose a new adaptive approach to the Under Secretary of Fisheries. In particular, the current management plan should re-examine the exploitation programme, which staring from early stages would result on immediate economic returns to the fishing association, due to the fifth year of operation on the original plan. This offers a totally different and attractive scenario for the local community, for which commercial exploitation of the red sea urchin fishery has been subject to a self-imposed permanent moratorium since 1998, producing no incomes since that time.

The sensitivity analysis proved to be a very powerful tool to understand and analyse interrelations between potential risks and opportunities, major outputs and targets. This allowed the occurrence of risk factors to be verified, and their influence quantified as a function of their probable variability distribution patterns. Also known as risk assessment, this methodology is an essential element on the bio-economic precautionary approach to fisheries management (Defeo *et al.*, 1997), offering a key tool for determining the uncertainty associated with critical assumptions prior to the implementation of decision criteria, defined on the basis of the risk associated with each alternative strategy. In this context the ‘assess risk’ module provided on Powersim Solver was shown to be very user-friendly and cost-effective in predicting the effect of uncertain factors on the results of the model, which also allowed actual risks and opportunities to be disclosed.

The outputs of the sensitivity analysis were interesting, as while some anticipated potential critical assumptions were revealed not to represent major risks, others firmly confirmed their critical influence on the system outputs, and a few other unexpected factors clearly showed their pattern of influence.

Natural mortality of released stock showed a relatively low influence over the economic performance of the project, incomes and total commercial stock. Despite natural mortality rates of stocked individuals was higher than for wild urchins, its potential estimated range of variation proved not to be critical to major outputs. Still, as confirmed on the single-variable optimisation analysis formerly described, an improvement the average survival rates towards those described by wild stock is a major issue to be sorted out before mass restocking can be viable and effectively applied.

In this context, in Chile all stocking experiments have focused their attention mainly on post-stocking issues such as: overall survival, growth rates, and to some extent inter-specific relations (competence and predation), leaving fundamental pre-stocking aspects such as site selection and size-at-release out of analysis.

In particular, optimisation of release size has been described as a key problem in management of stocked fisheries (Cowx, 1994; 1998). The optimum size will depend on the contribution that a particular size of released individuals will make to the catch or harvestable stock and on the resources required to produce that size (Lorenzen, 2000). However, such information is most difficult to obtain, due to the costs and efforts involved on systematic assessments (Lorenzen, 2000). Alternatively, allometric models to assess alternative release sizes, given an estimate natural mortality at reference size, have been developed allowing for cost-effective design of stocking exercises (Lorenzen 1995; Lorenzen *et al*. 1997). Implementing allometric mortality-size relationships for size release assessment, integrated to available economic information on hatchery operating costs, could be effectively used to estimate the optimum size for stocking the Chilean red sea urchin within the framework of AMEBR.

As expected, the three system objectives (TNPV, TGI and TCS) proved to be very sensitive to potential variability in natural mortality rates of wild stock and total natural recruitment. As noted in Chapter 3, these elements are probably the most uncertain and unmanageable factors in the system. Therefore, if a realistic prediction is desired, these factors should be seriously taken into account and analysed, as had been done in the strategic planning stage. Even though their variability pattern (normal or uniform) was known, and their level of incidence was confirmed and measured, it was acknowledged to be very difficult on the process to estimate their limits and potential variation.

Regarding natural mortality of wild individuals, the potential range of parameter uncertainty used returned a fairly wide standard deviation (50% the average value either side of it). Despite representing a rather safe and precautionary scenario of system behaviour for final simulations, it was highly acknowledged the need for a more realistic way to estimate potential variability of this parameter. Future studies may consider the integration of size-at-length data from different Base Line Studies to produce a comprehensive natural mortality dataset based on the 'linearized catch curve analysis' (Sparre and Venema, 1992), as it was done on this work. Unfortunately, as it turned up during this project, BLS contain highly sensitive information being to some extent confidential, and therefore unless a mutual cooperation agreement is reached with each specific fishermen association, accessing this data may be difficult.

In view of the great uncertainty and complexity involved, it was acknowledged that the methodology and limits used to deal with natural recruitment were fairly acceptable. Nonetheless, based on the outputs of the sensitivity analysis, which described what was probably the most critical assumption in the model, clearly the crucial importance of adequate assessment of this component was recognized. This may represent the only way for an accurate and realistic analysis of any management approach to be applied to this fishery. Confirming this, when describing the major constraints of analysing the efficacy of marine reserves for management of the Californian red sea urchin, Hilborn and Walters (1992) noted that no matter how many other mechanisms and factors are considered; the advisability of marine reserves depends critically on the relation between competent larvae and successful settling juveniles (parameter a) as a measure of natural recruitment, which is also unknown.

Describing a highly critical influence over major objectives, the average catch rate at the cove of Quintay showed a wide range of variation, confirming the fishing efficiency for benthic species to be very variable depending on the skill or the luck of the fisher (King, 1995). At this point however, it was also possible to disclose that this variability was mostly determined by the skill of the fishing crew, showing constant but differential effectiveness among the various crews at the cove. Based on a relatively small coastal areas, where natural stocks are very well delimited, and species movement is restricted, the catch efficiency during fishing operations will improve significantly, being increasingly better-planned, mechanized, and more consistent amongst fishing crews. Additionally, as the AMEBR system is implemented throughout the country, it would be expected to observe more stable landings and fishing rates, and uniform catch efficiency, reducing risk and variability in the system.

When restocking was considered within the management approach, the unit price of seed was revealed to be a highly critical factor, for the overall profitability of the project. Hence, the TNPV was strongly sensitive to a uniform variation on the cost of the restocking material.

Practical analysis of these outcomes should be based on the distinctive modest economic situation prevailing for most if not all coves in Chile, in terms of income and cash flow, and hence their limited capacity to pay for hatchery-reared juveniles to restock. In this context, the stocking material represents the most important restocking-related operating cost, which is very unlikely to be supported by artisanal fishing associations. Unless external sources of funding are available, mass restocking programmes are very unlikely to take place and ultimately succeed in the long term. Furthermore, based on the single-variable optimisation analysis, even if external sources of funding are available to support restocking programmes, given the actual mortality rates, restocking material would have to be 32% cheaper ($17/juvenile) than the actual average cost ($25/juvenile) to be a viable option.

In the case of the Quintay fishermen's association, the close relationship and long-term mutual cooperation agreement with the MRCQ allowed them to obtain the full first year release material free of charge. This represented a cost reduction estimated at 2.23 to 4.3 million pesos, based on a unit price of $25 to $50 (Vega and Figueroa, 2000) and a total of 85,000 juveniles released on 1999, when no incomes at all were been generated from the sea urchin fishery. This, may be contrasted with the total expected or historical incomes specifically obtained from the red sea urchin fishery at Quintay, where the operating restocking-related cost could stand for up to 21.50% of the total annual gross incomes of the cove, estimated at 20 to 23 million pesos (del Campo and Perez, 1999). Furthermore, if consider a total release of 140,000 juveniles, as it would be required with the lower recruitment level (25,000 individuals/year), seed related costs could stand for 3.5 to 7.0 million pesos, representing a more significant 30% of total historical incomes per sea urchin concept at the cove.

Confirming the precarious economic situation, as no actual funding source was found to further support the integrated restocking and management programme for the red sea urchin, no official request was placed before the Undersecretary of Fisheries, and no release of hatchery-reared juveniles was performed at the AMEBRQ during 2001 and 2002 (Association of Independent Artisanal Fishermen of Quintay pers. comm.).

In general, both the TGI and the TNPV proved to be sensitive to changes in the unit price of the product destined for both: national and international markets. Yet again this must be analysed in terms of the actual situation prevailing in artisanal fishing coves in Chile. As previously noted, wholesale landed prices for benthic resources are usually very changeable, being better described by a uniformly distributed pattern in time. Price dynamics are determined by the variation on landing volumes, whose magnitudes are independent of the price and depend on external variables (Palta, 1995). Thus, if the supply or offer dynamics is unstable, the effects on price behaviour will be the same.

From this standpoint, variation on the unit price would represent a very risky factor, highly critical in the short and long-term economic development of the project. However, this may not be the case for small-scale fisheries operating under the system of AMEBR, in which has been found that along with a significant improvement in product size, standard and quality, landings have increased and stabilized, offering a more constant supply (Castilla and Pino, 1996; Castilla and Fernandez, 1998). As a result, unit mean prices have improved significantly and steadily become more stable, in comparison to other coastal areas operating under an open-access regime (Figueroa *et al.*, 1998b, del Campo *et al.*, 1999, Subsecretaria de Pesca, 2000b). Since 1994 the application of management plans in Caleta Quintay has shown optimistic results for keyhole limpets and sea urchins stocks. Here, an increase of, higher size-classes, and an abundance of natural stocks in the AMEBR been observed. Consequently, the capture per unit of effort improved and important unit-price rises were observed between this site and historic fishing areas (Figueroa *et al.*, 1998a). These facts may indicate an optimistic prospectus for the whole commercialisation process and price dynamics for benthic resources, inducing a positive reduction of the variability and uncertainty.

The risk management process carried out in this research was crucial to develop strategic management plans for the red sea urchin fishery at Quintay. For this, the 'manage risk' task on Powersim Solver utilises a combination of the 'optimise' and the 'assess risk' (sensitivity analysis) tasks, with the purpose of finding the most robust policy to changes on assumptions (Saleh and Myrtveit, 2000). In this way, it was possible to find the best set of decisions (strategic plan) to achieve a given objective while keeping the risk below a given threshold.

In spite of the results and analysis of the deterministic case study-based run, the multi-objective 'manage risk' run outputs demonstrated that overall macro-scenario 3 was comparatively better than macro-scenario 1. For macro-scenario 3, excepting for the TCS target at year 5, output decision values achieved all of the system objectives with higher certainty levels than macro-scenario 1. Furthermore, decisions integrating these policies were fully realistic and viable management options capable of being applied in the real system.

In effect, the overall profitability of the project achieved a very high certainty (95%), while keeping the total commercial stock at most satisfactory levels (62%) and the TGI higher than the first management approach (19% versus 15%).

Despite the initial runs proved stocking to be economically unviable, when considering likely variation of uncertain factors macro-scenario 3 proved to be significantly more robust than macro-scenario 1. Based on the sensitivity analysis, where recruitment proved by far the most critical factor, this robustness was essentially determined by the extra supply of individuals to stock and constant support to a highly variable natural recruitment.

With an overall objective certainty level estimated at approximately 59% the adaptive restocking and exploitation macro-scenario described the best approach for long-term management of the red sea urchin fishery. In contrast, the traditional size and season restriction-based macro-scenario proved to be less efficient, returning a 56% of certainty for the achievement of major objectives.

However, given the economic (i.e.: high operating costs) and technical (i.e.: low survival rates) limitations conditioning stocking-based management cost-effectiveness and applicability, the question that remains is: can restocking be actually implemented as a major long-term management tool to support natural recruitment, recover overexploited stocks and allow for sustainable commercial exploitation of the red sea urchin in Chile? In other words, considering the substantial progress on the hatchery production process, and therefore seed availability; the suitable legal and institutional framework on property rights, and the promising socio-economic and biological prospectus for restocking sea urchins under the regime of AMEBR; is the Chilean fishery system proactive or promoting, and the artisanal fishery sub sector prepared to apply, this management tool? And if so, is the Government eventually capable to support economically and regulate its massive implementation? If not, which are the actual constraining factors? This issue will be further analysed in the final Chapter.

The 'manage risk' run outputs revealed an additional issue, previously noted on the GISRM Chapter, which is the over dimensioned size of the AMEBRQ in relation to both, the existing red sea urchin fishery, and the overall area suitable selected for restocking. In fact, regardless of the approach and macro-scenario analysed, all outputs pointed out that the original AMEBR (104 Ha) had to be reduced to achieve the optimum profitability of the project (TNPV>0) with expected certainty (85%). As a result, the optimum AMEBR sizes obtained ranged between a minimum of 33.43 Ha (Table 5.12, macro-scenario 1 on the second round strategic plan) and a maximum of 73.13 Ha (Table 5.11, macro-scenario 1 on the first round strategic plan). The optimum size for macro-scenario 1 and 3 were calculated at 57.08 Ha and 49.28 Ha respectively, returning a 90% and 95% certainty of achievement of the TNPV target on average.

Together with the outputs of the GISRM, this clearly showed that the AMEBRQ is oversized with respect to both the optimum prospective bio-economic performance and the actual spatial requirements associated to either a restocking-based or traditional management approach. However the red sea urchin is not the only targeted species in the area. As for most management areas in Chile, the AMEBRQ was requested and is currently operating for the management and exploitation of not one, but four different benthic species of commercial interest, including the "loco"-abalone and three keyhole limpet species. As a result, spatial requirements are significantly larger than for a single-species based regime, especially if considering that the sole potential inhabitable area for 'loco'-abalone was estimated at 1,009,210 m^2 representing 97.15% of the AMEBRQ (del Campo *et al.*, 1999).

Considering that the minimum size of the areas will be determined by the overall spatial requirements of multiple resources under management, effective reduction towards the bio-economic optimum is restricted; therefore long-term profitability comes down to an adequate reduction in the property tax rather than a size optimisation.

This may indicate the need to consider further the licensing and taxing system, as the current tax, to be paid by artisanal fishermen associations after the second year of operation of a given AMEBR, would be excessive in relation to total incomes based on actual productivity of the area. In this context, Stotz and Perez (1992) reported that the cost of the AMEBR licence was disproportionably high in relation to the theoretical production of a costal area, suggesting that prospective management areas and extensive aquaculture leases should receive a different treatment than those for intensive aquaculture. Moreover, the authors recommended a differential licensing and taxing approach based on the potential use and estimated production of each ecosystem.

This analysis points up the high influence of this factor into the long-term economic performance of the project. More importantly, although the AMEBR tax represents an external and uncontrollable factor to the fishery manager; it is a manageable element, which may be adjusted by relevant governmental institutions. Consequently, rather than a risk, the annual property tax represents a real opportunity factor, which may be modified so as to improve the socio-economic net benefits of the system of AMEBR in Chile.

Computer simulation models have been used for several years to support and guide decision-making in the salmon aquaculture industry, specifically designed to analyse policy decisions about hatcheries and to estimate the contribution to fish catch and escapement of alternative harvest regulations, or to predict changes on stock abundance (Rettig, 1987). McCarl and Rettig (1984) developed a simulation model to analyse the trade-offs between short-term economic interests and long-term conservation goals. Although all these models were presented to a forum especially interested on improving the usefulness of bio-economic information in fishery management, such as the National Fisheries Service, neither model appeared to have influenced any policy decision (Rettig, 1987). In determining the reason for this, Rettig (1987) diagnosed the lack of integration among the agents involved in the fishery system (social scientists and fishery managers), when developing bio-economic models for fishery management. The author concluded that although fishery managers want help from economists and other social scientists, policy analysts providing information, either as numerical results or computer-based bio-economic models, must acknowledge that managers will inevitably combine this information with their own common knowledge.

From this perspective, the objectives of the final stage of this research were to diagnose the real need for decision-making support tools, to evaluate the hardware and technical capability of relevant agents, and to train, use and ultimately assess the global application of BSESM in terms of the level of understanding, practical operation and acceptation degree by targeted users. This process was aimed at involving local fishermen and fishery managers in the modelling process and model implementation, gaining their interest and active participation on criticising the model, and ultimately getting them to, explore, operate and report results of model experiments by themselves.

In order to achieve these objectives, the issue was approached through a field-based integrated programme involving, marine scientists (staff MRCQ), fishery managers (technical support unit of the Association of Independent Artisanal Fishermen of Quintay) and fishermen representatives (director and other members of the local Fishermen's Association).

The outcomes of the opening discussion groups clearly set out the actual need for tools or methodologies for management of the red sea urchin fishery within this sub sector. This was shown by two different, but linked causal factors. The first, was the lack of cost-effective and applicable methodologies to design, per-evaluate and monitor management plans by fishery managers and resource users, as represented by the local fishermen's associations and their technical units. Unlike the other benthic resources under management at the AMEBR ('loco'-abalone and keyhole limpet), there is at the moment no standard technique or quantitative methodology to estimate and design restocking programmes or management plans in general. Accordingly, the second major factor was the resulting insufficiency of quantitative technical, biological and socio-economic data; essential to design, analyse and support management plans for approval through the Under Secretary of Fisheries.

This is probably the major factor constraining the inclusion of the red sea urchin resource for coastal management in most of the AMEBR. In fact, despite it being widely distributed and historically exploited along the Chilean coast, most fishermen's associations have avoided dealing with this important commercial resource in their management areas (Association of Independent Artisanal Fishermen of Quintay pers. comm.). The lack of standard quantitative methodologies has also been demonstrated by the highly inconsistent pattern of the assessment process, in terms of both the quality and structure, and the production design of the management plans successfully approved to different coves by the Under Secretary of Fisheries (Association of Independent Artisanal Fishermen of Quintay pers. comm.). As confirmed by relevant agents, analysis and judgement of proposed management plans is mostly based on common knowledge and some rather simplistic calculation on the basis of the historical captures in relation to the management strategy (Montesinos pers. comm.).

The field-based assessment of technical capabilities and hardware infrastructure required for using the simulation model or similar supporting tools, proved to be generally positive. At the administrative office two PC computers and essential peripherals were kept and used on a daily basis by the technical support unit, the secretary and various members of the association. In general the agents proved to have more than sufficient computing skills. However it is important to note that this may not be the case for all artisanal coves in Chile, as the Cove of Quintay is a highly organised and one step ahead of atypical 'caleta'. This situation should be carefully considered when introducing, the BSESM elsewhere.

Fishery managers and fishermen's representatives at the study area showed a fairly good level of understanding of the model's underlying theories, fundamental structure and basic operation. As the BSESM was fully installed and tested on the computing systems, target agents had the opportunity to explore and utilise the software to its full extent. In general, this group of fishermen, although not having high education levels, showed themselves to be very well informed regarding management issues, scientific terms, and both biological and economic theories applied to marine benthic populations and small-scale fisheries in general. Yet again, this may be an exception within the sub sector in Chile, so other coves may require further tutorial input prior to the introduction and use of the software. However, in most cases fishermen's representatives are fully involved in the entire process of developing, implementing and monitoring managements and exploitation plans for target resources within the AMEBR system. Hence, most of the coves currently involved in the system require, and have adequate levels of understanding and knowledge, on the basic premises applied. Artisanal fishing associations are enforced by law to be supported by a technical unit when planning, implementing and monitoring management plans for the target resources at the AMEBR assigned to them (Servicio Nacional de Pesca, 1996).

The BSESM was mostly welcomed and accepted by fishermen's representatives, technical unit staff and fishery scientists at the study area. Local fishermen were very enthusiastic during the learning process and when using the BSESM, but more importantly when visualising the real possibilities and potential benefits of its use. This response relied on the agreement of mutual cooperation, development and feedback with the local association, which was established and improved from the very early steps, while studying and modelling the system, to the final stages of this research project, when running and implementing the simulation model at the study area.

While proposing an adaptive approach to fishery management, Walters (1986) noted that models are often effective only when fishery managers are directly involved in the modelling process, but fewer contributions are forthcoming when models are developed by experts and results reported to the managers. Accordingly he recommended that the process of fishery management and the scientific investigation to be merged. Not underestimating the importance of model reality, generality and precision, it was highly acknowledged that unless the model and their management proposals are well understood and accepted by fishermen, successful implementation is unlikely to take place. As described by Pringle (1985): 'scientists and managers must present new concepts and resource-based science to their 'clients' in a lucid way, and once mutual understanding is developed, good resource management can follow'.

In broad terms, the implementation of the BSESM in Quintay was a successful venture. Although, this work was developed with a single small cove during a short period of time, the projections towards a more integrated longer-term use are encouraging. This is supported by the economic importance of this benthic resource, its state of over-exploitation and the genuine will for rational management. Therefore, there is a real need for decision support tools that cost-effectively allow for alternative resource management planning and evaluation, and for these to be developed within a very suitable technological setting and legal-institutional framework. The wider and fully effective application of the BSESM will be subject to a positive recognition, acceptance, but more importantly legitimisation by relevant governmental fishery departments regulating the system of AMEBR. This issue will be further discussed in the final section.

CHAPTER 6

GENERAL DISCUSSION

6.1 THE PRESENT STUDY

This study focused on the management of the red sea urchin *Loxechinus albus* fishery in Chile. The main objective was to design, construct, implement and assess a computer-based simulation model to analyse the biological effects, socio-economic consequences and spatial dynamics resulting from coastal management plans applied to this resource under the system of AMEBR. This was accomplished by using systems dynamics (SD) and geographical information systems (GIS) modelling, in a process of model development, run, optimisation, sensitivity analysis and risk management, and a series of field-based activities carried out at the cove of Quintay. This work shaped a cost-effective and flexible tool to support decision-making in policy design, pre-evaluation and analysis of management plans for the target species. In addition, two optional (traditional size/season restriction and restocking-based approach) long-term management plans were designed, analysed and proposed for the red sea urchin fishery managed at the AMEBR operating at the study area, at the cove of Quintay, Chile. Finally, this model allowed the projections for traditional management versus restocking-based enhancement activities to be analysed, as a major long-term management strategy to recover natural stocks and allow for sustainable exploitation at commercial level.

6.2 BIO-SOCIO-ECONOMIC SD AND GIS MODELLING FOR FISHERIES MANAGEMENT

Fishery management is ‘the pursuit of certain objectives (biological, social and economic) through the direct or indirect control of effective fishing effort or some of its components’ (Panayoutou, 1982). Because of its control feature, fishery management is thought to be required when fishery becomes overexploited. Once management objectives are reached, specific objective-orientated measures and policies must be designed, planned, implemented, monitored, evaluated, and re-designed if necessary. This is significantly complicated due to the occurrence of multiple objectives involved when evaluating the performance of a fishery system. Management strategies must be aimed at maximising economic returns, but also at sustaining the biomass of species targeted above minimum levels (Seijo *et al.*, 1997). The presence of uncertain factors in the external environment, such as a highly variable recruitment or natural mortality or price fluctuation, makes the manager’s task even more difficult.

The multi-objective simulation and optimisation modelling approach conducted in this study has been recently used for policy design and management of a number of fisheries with technological and ecological interdependencies (Diaz de Leon and Seijo, 1992; Seijo *et al.*, 1994a). Within this framework the application of SD science has been acknowledged as a solution to approach fishery allocation and systemic management of fisheries (Manatesh and Park, 1982; Seijo, 1987, 1989; Seijo and Defeo 1994b). Accordingly, there has been a widespread attention in using modeling approaches to a variety of systems (Bennet and Cholerey, 1978), including functional/deterministic and 'black-box' stochastic models (Muir, 1996).

The use of SD multi-objective simulation models provides methodologies and specially designed tools (scale-models) to study fishery systems that permit the reconstruction of the complexity of the system or phenomenon, without an intervening formalization (le Fur, 1999). There is little doubt that these models can be very useful in understanding the interrelationships in and between systems. However they may also be misused, and should be used to inform rather than legitimize management or policy decision (Constanza et al., 1993).

In this context, the BSESM and the GISRM developed on this study must be considered as an integrated tool that provides outputs to a range of input data specific to a red sea urchin fishery occurring at a given AMEBR. This means that it represents an aid to support decisions, which fishery managers may ultimately make on the basis of this and other relevant sources of information, including literature searches, direct communication with experienced individuals or agencies, or simply by using their own common knowledge. Accordingly, model outputs constitute new information that must be added to and verified with existing knowledge of the actual fishery system, in order to be effectively implemented.

This study, however, has shown that the real power of SD simulation is the possibility to project and explore multiple scenarios, offering the manager the ability to define what may happen in the future and then choose among alternatives.

In addition, the GIS modeling approach employed in this study proved to be extremely powerful tool for spatial resource planning and management, when applied to site selection for restocking benthic species. This confirmed the great potential of GIS to support decision-making in coastal systems, representing more than just a mapping tool, a cost-effective device for management modeling of spatial components in a virtual environment.

The combination of bio-socio-economic SD and GIS fishery modelling methodologies used on this study proved to have a great potential as an integrated approach, interrelating biological and socio-economic factors with spatially-referenced components that interact in dynamic ways in the highly complex marine systems. On top of the specific outcomes and valuable contributions of the GISRM by itself, the use of GIS modelling allowed the spatial component to be introduced into the system's dynamic simulation, analysis and projection. This represents a significant contribution towards the development of more comprehensive bio-economic models for analysis of fishery systems, which is especially required when dealing with marine benthic species or sedentary resources in general. Future studies should be focused on the design of not only of one-way data flow integration, but also including feedback processes, i.e.: transferring data and information between a GIS-based and a SD simulation model in both directions. This will allow the dynamic analysis to be introduced explicitly in the GIS modelling, as for example: showing the time-series spatial representation of the performance of a restocking programme or an exploitation policy over the stocks of a given coastal area, given that the data is externally provided by the BSESM and imported into the GIS system.

6.3 UNCERTAINTY AND FISHERIES MANAGEMENT

The results arising from this study depended on a number of parameters and critical assumptions (uncertainties), the value of which may well change in the future. Such evolutions can affect the evaluation of restocking or traditional based management programmes either positively or negatively. These changes may affect not only biological and economic parameters, but also the priorities as perceived by public opinions, among which environmental preoccupations have become obviously more important (Laurec, 1999). Uncertainties in predictions have been categorised into: noise, as referred to random variation on outcomes, often linked to external variation; uncertainties about the present state of the resource system, often determined by a wide range of attributes covering human components to technical aspects, and uncertainties about the behaviour of the system, namely the dynamic response to change which always remain uncertain (Lorenzen and Garaway, 1998)

However, as this study developed am interactive and flexible dynamic model, if the fishery manager is able to anticipate changes, this may be effectively included in the simulation. In this context, the systems optimisation methodology used in this study, namely ‘risk-taking’ (through the ‘manage risk’ module available on Solver), to find the most robust policy under variation (uncertainty) (Saleh and Myrtveit, 1999), is been considered new contribution in the field of SD. Policy robustness is a vital issue for strategic planning and management in any field or modelling application. The model optimisation software and underlying methodology used on the final stage of this work proved to be a very cost-effective and easily run way to find and investigate robust policies for long-term management of the red sea urchin fishery.

According to Opaluch and Bockstael (1984), although bio-economic models are analytically useful for yielding insights into the nature of fisheries problems and characterising the optimal solution, numerical results from their application do not offer much confidence. This is due to the overwhelming uncertainty about fisheries dynamics, which is particularly troublesome from a management point of view. The authors suggested that an appropriate goal for fisheries management would be the achievement of an acceptable (‘satisfying’) range of target levels of effort and the determination of approximate biological, social and economic minimum requirements in defining that target.

Despite being a dynamic bio-economic approach to fishery modelling, the present study was essentially based on this principle. Accordingly, rather than optimising management policies towards a biological or socio-economic optimum, the whole strategic planning process was conducted on the basis of explicitly defined minimum requirements. Furthermore, the final optimisation process, ‘risk management for strategic planning’ also took into account the potential variability (uncertainty) of risks in the system and returned numerical outcomes with a quantifiable and known level of confidence.

The ‘satisficing’ approach to management may result in a subjective choice amongst a set of policies (Opaluch and Bockstael, 1984). However, such decisions, may be more effectively implemented, as they were defined in terms of a realistic target rather than an optimum mark. In addition, the application of this approach may be more efficient if considered from early model development and run to policy design and decision-making. This is especially relevant when dealing with an imperfect, uncertain and even deficient fishery system, where input data usually is not accurate nor widely available, regulations are not suitable, and management effectiveness will ultimately rely on fishermen’s perception and preferences, level of understanding, agreement and response.

Thus, rather than perfect conceptual models, optimum decisions and ideal policies, what is required is applicable and cost-effective models, realistic and workable decisions and long-term policies suitable to be implemented in a real and somewhat imperfect fishery system.

Uncertainty may also be effectively acknowledged through the so-called 'adaptive approach to fisheries management and development' that recognises the lack of control by analysts and planners, and emphasises stakeholder participation and learning from the management experience to deal with uncertainty and achieve expected outcomes (Holling, 1978; Berman, 1980; Walters, 1986; Lorenzen, 1995; Lorenzen and Garaway, 1998). On the basis of the adaptive approach guidelines to development of stocked fisheries under uncertainty outlined by Lorenzen and Garaway (1998), the methodology developed in this study may be well fitted within an adaptive approach for red sea urchin management. This process considers 6 major stages, starting with the (1) definition of wider development objectives, followed by (2) an initial diagnosis of the resource system, and the (3) definition of immediate objectives and the identification of possible courses of action. Then, having defined the possible courses of action is necessary to (4) predict the potential outcomes and to identify dynamic uncertainties associated. If dynamic uncertainties are high, it is required to reduce them by implementing adaptive management, and hence (5) actions should be taken to produce necessary information. Adaptive management can be passive, allowing natural variation in management, or active, deliberate examination with management. Finally, it is constantly required to (6) assess the outcomes and feedback the system.

The present study comprehensively developed the five first stages, and proved to be extremely cost-effective in predicting the outcomes of management strategies, and returned the range of decisions under explicit consideration of uncertainties. Still, as the system showed high dynamic uncertainties (e.g.: recruitment, natural mortality, product-price, property tax, seed cost, etc) the implementation of an adaptive management would be essential (Lorenzen and Garaway, 1998) in order to achieve the desired outcomes. As recommended by the authors, having the ability to understand and predict the outcomes of various management strategies (e.g.: through efficient use and implementation of the BSESM), implementing an adaptive approach for actual management of target resource (e.g.: long-term management of the red sea urchin fishery) will require learning procedures involving stakeholders (e.g.: artisanal fishermen associations and governmental institutions (Subsecretaria de Pesca)), active experimental management (e.g.: research institutions

(MRCQ)) and monitoring (e.g.: technical supporting units and artisanal fishermen associations).

The combination of the ‘satisficing’ to define fishery targets, the ‘manage-risk’ methodology to search for robust management strategies and the ‘adaptive’ approach for actual implementation of a management plan for the red sea urchin or any other benthic fishery in Chile, may provide a way to deal with the great uncertainty and variability related to major biological, economic and social factors in the system, and ultimately to achieve long-term sustainable management within the AMEBR system.

6.4 PROJECTIONS OF RESTOCKING FOR RED SEA URCHIN MANAGEMENT IN CHILE

Over and above of the quantitative outcomes obtained from running the GISRM (suitable and available restocking sites) and the BSESM (alternative strategic management plans), the case study-based analysis made it possible to disclose the wider issues related to the red sea urchin coastal management.

These results demonstrated the biological inefficiency of traditional size/seasonal restriction-based approach (macro-scenario 1) for sustainable management of the target species. More importantly, final outcomes strongly suggested that a combination of adaptive restocking-based enhancement activities and flexible exploitation constituted a highly attractive approach (macro-scenario 3) for stock management of this fishery. In addition, when considering likely variation of uncertain factors macro-scenario 3 proved to be significantly more robust than macro-scenario 1. This robustness was essentially determined by the extra supply of individuals to stock and constant support to a highly variable natural recruitment. According to this, mass restocking of hatchery-reared juveniles together with suitable coastal management regulations may offer the best way to recover and sustain major stocks of this important benthic resource in Chile.

However from the economic analysis, stocking was also found to be economically unfeasible, being a rather cost intensive exercise negatively affected by high natural mortality rates. A single-variable optimisation analysis demonstrated that a higher survival rate is needed to generate sufficient profits to cover major restocking costs and a positive payment, or a cost reduction is essential to make up for the loss.

On top to these practical constraints, based on the distinctive modest economic situation prevailing for most Chilean coves and hence their limited capacity to pay for stocking material, unless adequate and constant funding is available to support artisanal associations, they are very unlikely to develop mass release programmes.

For this reasons, wider implementation of restocking activities for the red sea urchin in Chile is subject to a good acceptance, promotion and full financial support by relevant governmental institutions, but also to significant technical improvements allowing for higher survival and recapture rates on stocking exercises and costs optimisation on seed production.

In a broad sense, this situation may be well exemplified by the Japanese experience. Japan is probably the country with the longest tradition on cultivating marine organisms (Hallenstvedt, 1999), in which enhancement programmes cover a large number of species of fish and shellfish (Suda, 1991). Here, stock enhancement programme has been developed, promoted and financially supported by the government since 1963. At the present, there are 16 national and 157 local government hatchery facilities distributed in the coast of Japan, in which around 90 species are under technical development for stock release (Inamura, 1999).

Although fisheries, political and societal conditions vary in each nation; a 30 years history still under development clearly shows the level of compromise and mutual cooperation between government, regional authorities and fishermen cooperatives that is required to promote and successfully implement a massive enhancement policy for supporting coastal fisheries. More importantly, this also involves a combined and not insignificant financial effort to cover the administration operations costs among all parties, e.g.: representing 115 million Yens (≈U$925,000) at the Aomori prefecture in 1987 (Inamura, 1999).

Although the Chilean government has mostly supported the cost of the BLS to develop MEP, representing to the date more than five hundred million pesos (≈U$670,000) (Subsecretaria de Pesca, 2000b), there is undoubtedly a long way to go before alternative management, such as mass restocking, to be fully funded by the state.

Apart from the actual technical-economic constraints, there are also other relevant issues to be resolved before wide implementation of restocking programmes can take place in Chile. As the exploitation of benthic invertebrates is driving many resources almost to extinction, many efforts have been made to restock them. Many questions regarding these efforts have arisen among the scientific community, such as: where to get the parental stock from?, how do these interventions affect genetic variability?, are these risks of transmitting pests or diseases?, which biological-ecological-environmental aspects need to be considered for success?. These questions well reflect the concerns regarding the potential genetic, disease and ecologic impacts associated to restocking, currently prevailing in relevant stakeholders in Chile, and also widely discussed within the scientific communities worldwide.

Within this framework, it is too naive to consider that the release of artificially produced juveniles would have no consequences on the natural stock or the rest of the ecosystem, and assessing the ecological impact of restocking activities may well remain one of the most difficult elements (Laurec, 1999). The same author, however, underlined that: ‘it would be unwise to block any enhancement attempt because of potential genetic problems’, and ‘even in those parts of the world where people are not obsessed by genetic pollution, scientists should address it’. Finally, he noted that ‘stock enhancements have contributed to the development of techniques, which at least in some circumstances, can facilitate restoration of stocks facing the most severe risk in terms of genetic: extinction.

As restocking exercises are increasingly promoted and applied by several fishing associations in Chile, it has become imperative to analyze these issues. Accordingly, later in 2002, relevant agents and scientific forum will meet at the ‘International workshop on restoration on benthic invertebrate populations: genetics, diseases and ecology’ to be held at Coquimbo. The aim of the workshop is to gather people from different disciplines, which are contributing to the knowledge necessary for successful restoration or restocking, in order to analyze the state of the art, to review some case studies and discuss the basis for necessary regulations of these restoration efforts.

Given the economic (i.e.: high operating costs) and technical (i.e.: low survival rates) limitations conditioning stocking-based management cost-effectiveness and applicability, wide implementation of mass releases as a major approach for management of the red sea urchin fishery is very unlikely to take place in Chile. This will be subject to further research to support this approach, mostly to demonstrate its overall cost-effectiveness and quantify its potential ecological impact on natural stocks and communities. Additionally, governmental fishery agencies will require the generation of more specific regulations to control its design and implementation, and provide constant technical support for fishing associations before and during the process.

Still, this management approach must not be discarded as a prospective viable option within the Chilean perspective, mainly because of the:

- state of overexploitation of major natural stocks and the urgent need for recovery plans and rational management;
- socio-economic relevance of this benthic resource for artisanal fishing communities;
- positive biological projections predicted for this approach as analysed on this study;
- remarkable technological development and progress on hatchery processes;
- current investment on hatcheries able to supply mass seed on constant basis, and its potential for development of internal economies, additional labour source and diversification of fishing activities,
- suitable and improving legal-institutional fishery framework supporting ownership rights for management of benthic fisheries;
- encouraging results obtained on increasing experimental and some mass restocking exercises showing better survival and recapture rates;
- increasing interest and actual implementation of restocking programmes by artisanal fishing associations, and the
- growing attention and consideration of restocking as an available tool among relevant fishery agents and scientific community.

The benefits of stocking in Chile may also include social cohesion, the opportunities to create a community-based system with limited transaction costs, and better compliance in fishing wild and stocked resources.

All in all, these conditions may indicate a positive prospectus for at least localised implementation of restocking programmes within the short-term. This approach is likely to be successful in small, but well organised coves managing a red sea urchin fishery under the system of AMEBR, based on a positive agreement with seed producers or financial support to cover major related costs.

Effective performance of this approach will require a good level of understanding and acceptance, compromise and active participation of fishermen in all activities integrating the management plan, from the design and implementation to monitoring and re-design.

6.5 PROSPECTIVE USE OF THE BSESM AND ITS IMPLICATIONS FOR MANAGEMENT

The field-based assessment projected a positive perspective for the widespread use of the BSESM in the future. However, it was also acknowledged that this would be subject to adequate recognition and acceptance, but more importantly legitimisation by relevant governmental fishery departments regulating the system of AMEBR.

Given the previous assumption, during the last fieldwork the BSESM was introduced, explained and analysed with the department of AMEBR in charge of reviewing and judging all official requests, BLS and MEP presented throughout the country. During two meetings held at the Undersecretary of Fisheries head offices in Valparaiso, the participants mostly acknowledged the potential usefulness of the BSESM for artisanal fishing associations. In addition, they proved to be very receptive, recognising the lack of proper standard methodologies for design and assessment of MEP. However, it was also acknowledged that the potential benefits of using the software were above all for the resource managers and users, rather than for themselves as regulatory and assessing agency.

Despite their goals, namely setting the technical standards, regulating and controlling their fulfilment, and assessing and monitoring management plans on the basis of safeguarding sustainable use of resources inside AMEBR, they are constantly evaluating the feedback on the artisanal fishing sub sector and supporting pertinent modifications, which may improve the global performance of the system (Subsecretaria de Pesca, 2001). The Undersecretary of Fisheries is therefore open to make use of new information and methodologies to be provided by resource users and/or specific studies. On this basis, the BSESM has a fairly good prospective for its insertion as a recognised supporting tool for red sea urchin management within the sub sector and relevant agencies.

The use of the BSESM by artisanal fishermen associations in Chile may result in direct and indirect implications for management of the red sea urchin, which can also be divided according to their short or long-term incidence.

Short-term direct implications are those strictly associated with the actual and current use of the simulation model for design, pre-evaluation and proposal MEP for a given sea urchin fishery by the local fishermen's association before the Undersecretary of Fisheries, such as the one at Quintay AMEBR 'Sector B'. As a result, if the MEP is approved, major decisions integrating the strategic management plan will be implemented. This situation is obviously the final target of this work; namely the wide effective use and also actual implementation of the outcomes of the BSESM to support management of the target species.

Short-term indirect implications refer to the potentially increasing inclusion of the red sea urchin for management within AMEBRs along the country. This depends on the simulation software being adequately circulated and promoted of the within the sub sector and key agents. Accordingly, if specific well-known coves are successfully able to use and implement the BSESM to propose and ultimately get approval for their specific sea urchin MEP, other associations may be attracted to the idea and encouraged to follow their example. This may be the way to promote active participation of fishing associations into a rational management for the target species in Chile, by providing them with a tool to facilitate a usually technically complicated and highly bureaucratic process, as is the case for the design, request and authorization of the management plan. Moreover, as more fishing associations start to present MEP proposals based on the application BSESM for their AMEBR, the Undersecretary of Fisheries will progressively start to acknowledge this tool, understand and analyse their results and eventually legitimise its use to support management of the red sea urchin.

Long-term direct implications concern the biological effects on populations, and the socio-economic outputs of the BSESM strategic management and exploitation plan implemented at a particular coastal area. In this context, it is important to keep in mind the impact of this simulation software if is well introduced, accepted and widely applied to support decision-making for specific-resource management. Accordingly, its application must consider the availability technically capable users, good quality input data, but more importantly a sensible analysis of model outputs to support rather than legitimise management strategies.

Good quality input data not only refers to complete, accurate and actualised information, but also to specific datasets for target area on a suitable scale and resolution. Here, it is important to note that although some species-specific input parameters (e.g.: growth and reproduction) may be extrapolated from one coastal area to another, most input data, whether biological (e.g.: abundance and distribution of natural stocks, natural mortality and recruitment), fishery (e.g.: fishing pressure and capture per unit of effort), socio-economic (e.g.: costs, incomes, fishermen requirements and expectations) or spatial (e.g.: resource distribution, and available areas for restocking), must be AMEBR-specific.

This study presents a methodology and offers a tool to design, evaluate and optimise coastal management plans for the red sea urchin in a dynamic, interactive, systematic, integrated and flexible way. The optional strategic management plans proposed on this study may not be applied equally to any AMEBR, as they are the outputs arising from a single cove-specific analysis. Still, the complete methodological framework and analysis procedures developed may be applied to run the BSESM and optimise management of a red sea urchin fishery at any other AMEBR case of study.

Specific input data essential for running the simulation model should be available or easily gathered at any artisanal fishing cove managed within the system of AMEBR in Chile.

Furthermore, necessary hardware infrastructure and technical human resources may in most cases be provided by technical units supporting fishing associations.

Consequently, this tool should be accessible, properly used and implemented for sea urchin management support at most AMEBR-operating coves in Chile.

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APPENDIX 1

Questionnaire of scoring and weighting procedure for restocking site selection of sea urchin *Loxechinus albus* in the AMEBR of Quintay, Chile

Introduction

The aim of the following questionnaire is to gather specific information essential to run a Geographical Information Systems-based model for selection of sites for restocking (GISRM) red sea urchin juveniles in the AMEBRQ.

When restocking, there is a range of determinant factors that influence the effectiveness and ultimate success of the activity. The model objectives were achieved by the selection of determinant criteria influencing restocking activities. These were considered as three GIS-based models (species requirements, operational factors and area availability), which were built based on hierarchical structures.

In this model, the first group of factors is integrated by biotic and abiotic elements, which interact in highly variable, dynamic and complex systems such as the intertidal and subtidal coastal zones. These factors are species specific and their combination determines the life-stage's natural distribution. For this reason, these criteria were used in terms of the species requirements to identify suitable habitat for development in open natural environments.

The second, but also important, group is formed by those technical practicalities associated with the restocking exercise itself, considering land-based and aquatic, each with important physical constraints. Operational factors are considerable and can eventually determine the success or failure of a restocking practice. Hence, the combination of these criteria was used to estimate the feasibility for restocking in a given site.

Finally, the last group of criteria relates to the actual area to be used for restocking. Thus, even if a given coastal lease may be highly suitable and technically feasible for restocking sea urchins, its effective area may be limited by the natural distribution of wild stocks of the same or other benthic species. As a result, the spatial coverage of natural resources in the coastal area is essential to estimate effective area availability for realistic implementation of a restocking programme.

Species requirements submodel

Bathymetry[1]

Vertical distribution of sea urchins is determined by a number of biotic and abiotic factors. Among the latter, water depth is clearly one of the most important factors, and so it can be effectively used to define suitable areas depending on the species-specific requirements.

Please provide a suitability score, (scale: 1 to 10 points, where 0: minimum and 10: maximum) to water depth intervals in the study area (Fig. A.2) on the basis of a maximum depth of 50 m.

Water depth (m)	Score (1 to 10 points)

Seabed type

Type and condition of local substrate is also a very important abiotic factor, which determines amongst other things, recruitment, growth and general development of echinoids (Birkeland and Mesmer, 1978; Lang and Mann, 1976). This habitat requirement can be related to the particle composition of the substrate, as well as on other characteristics, such as its algae coverage or morphology.

Please provide a suitability score, (scale: 1 to 10 points, where 0: minimum and 10: maximum) to the following types of seabed existing in the study area (Fig. A.3).

Type of seabed	Score (1 to10 points)
Sand and grave	
Ball-type rock	
Volcanic-type rock	

Coastline exposure[1]

Together with bathymetry and seabed composition, coastline exposure is the third, and possibly the most relevant, abiotic factor regulating the distribution and development of the red sea urchin *L. albus* (Bustos et al., 1991). This applies to most benthic resources of commercial interest in Chile, such as "loco"-abalone and key-hole limpets, which mostly inhabit highly windy and wave-exposed areas in the North and Central coast (Barbieri and Silva, 1996). Consequently, these areas represent the most suitable sites for restocking of benthic resources.

Red sea urchin natural stocks distribution

Studies on sea urchins have reported important positive relationships between recruitment and survivorship of juveniles and adult densities, showing that recruitment development appear to be better around or under adults (Moore *et al.*, 1963; Ebert , 1968; Tenger and Dayton, 1977; Schroeter, 1978; Sloan, 1980). It would also appear that any restocking programme will probably have greater success if based upon sites where major groups of wild individuals exist naturally. The distribution of all existing natural substocks of sea urchins was therefore assessed as a key biological criterion for selection of restocking sites.

Weighted combination 1

Please provide weights of importance, in terms of percentages (%) for each of the four criteria forming this submodel, bathymetry, seabed, coastline exposure and red sea urchin natural stocks distribution. This will be combined in order to produce a quantification of the optimum sites for restocking sea urchins at the AMEBRQ based on of the species requirements.

Criterion	**Weight of importance (%)**
Bathymetry[1]	
Seabed	
Coastline exposure[1]	
Natural stocks distribution (sea urchin)	
Total	**100**

Operational factors submodel

Bathymetry[2]

When performing a restocking exercise for sea urchins, a number of procedures depend upon diving and shore-based operations. Practical implementation and the success of these operations is influenced by water depth. Water depth will therefore determine the type and complexity of operations for seeding and management of restocked individuals, and will influence the practical efficiency of any restocking programme.

Please provide a suitability score, (scale: 1 to 10 points, where 0: minimum and 10: maximum) to water depth intervals on the basis of a maximum depth of 50 m.

Water depth (m)	**Score (1 to 10 points)**

Coastline exposure[2]

As with water depth, the relative exposure of the coastline will constrain a number of operations when restocking. This is particularly relevant in the case of the red sea urchin, as it requires work at highly exposed shores. Here, operations such as diving, sampling, harvesting, and reallocating, will be determined by oceanographic conditions and the degree of wave exposure.

Accessibility by land

In general, intertidal zones in the Central coast of Chile are not easy to access. Here, the shoreline has an abrupt topography, including cliffs and rocky elevations across the sea-land boundary. As restocking involves a number of land-based procedures; accessibility to selected seeding sites is a major operational factor. These procedures include transporting of inputs, seeds, various devices and the working team to the site. It is particularity important to move the seed safely and quickly, and ease for a site will be a key factor in successful restocking, further allowing on-site operations such as monitoring, sampling, redistribution, etc.

Accessibility by sea

Site access by sea was also identified as a major factor influencing restocking, as a variety of input working materials; divers and sometimes even juveniles need to be transported to the specific site by sea. A site that is located in close proximity to a boat ramp or beach is preferable, in order to facilitate site access and transportation (Arnold *et al.*, 2000).

Weighted combination 2

Please provide weights of importance, in terms of percentages (%) for each of the four criteria forming this submodel, bathymetry, coastline exposure, accessibility by land, and accessibility by sea. This will be combined in order to produce a quantification of the feasible sites for restocking sea urchins at the AMEBRQ based on the operational factors involved.

Criterion	**Weight of importance (%)**
Bathymetry[2]	
Coastline exposure[2]	
Accessibility by land	
Accessibility by sea	
Total	**100**

Weighted combination 3

Please provide weights of importance, in terms of percentages (%) for each of the two submodels forming the GISRM, species requirements and operational factors. This will be combined in order to produce a quantification of the suitable and feasible sites for restocking sea urchins at the AMEBRQ.

Submodel	**Weight of importance (%)**
Species requirements	
Operational factors	
Total	**100**

Selection of restocking areas

Based upon your own knowledge and experience, please select specific locations (on Figure A.1), which you think, may describe suitable characteristics for implementing a restocking exercise.

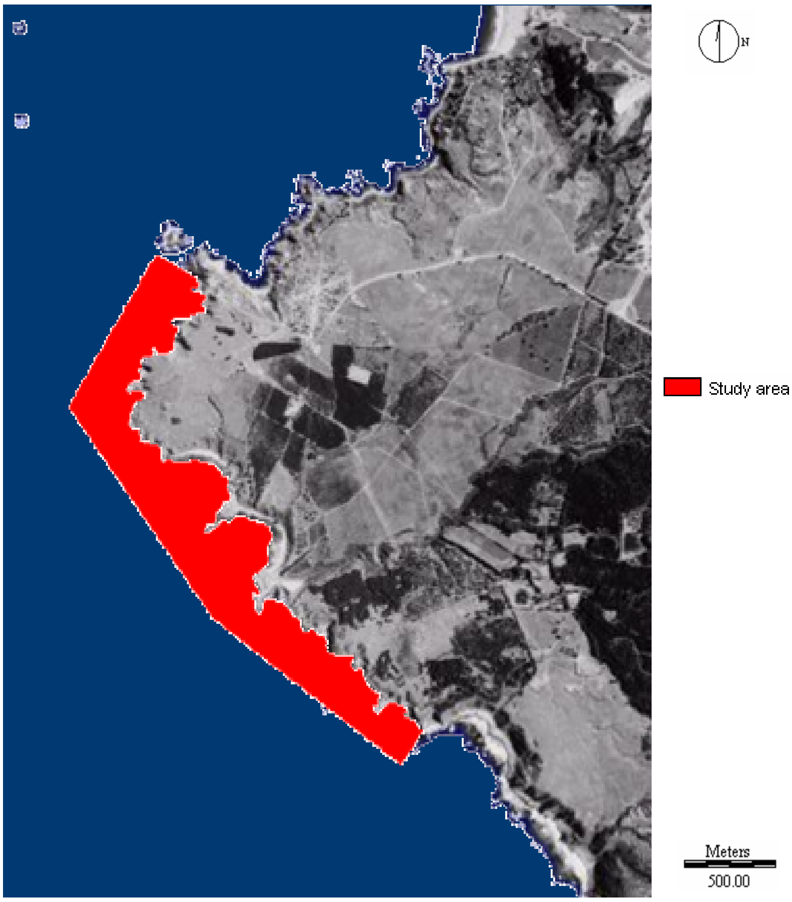


Figure A.1:Study area (AMEBRQ)

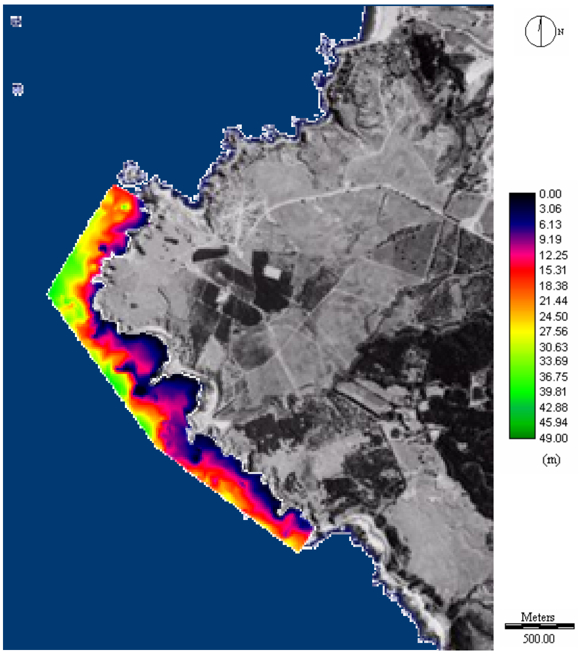


Figure A.2: Bathymetry of the AMEBRQ.

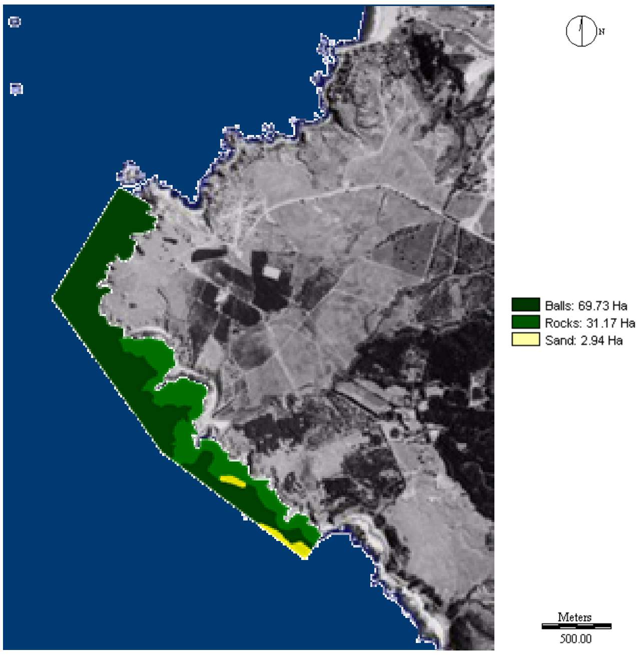


Figure A.3: Seabed composition of the AMEBRQ

Results Questionnaire of scoring and weighting procedure for restocking site selection of sea urchin *Loxechinus albus* in the AMEBR of Quintay, Chile

Table A.1: Scores assigned to specific criteria by experts interviewed.

Species requirements submodel					Operational factors submodel		
	Water Depth (m)			Type of Seabed	Water Depth (m)		
Score	Stotz, W.	Figueroa, M.	Perez, H.	All authors	Stotz, W.	Figueroa, M.	Perez, H.
1	20-+50		-	-	-	45-+50	25-+50
2	-		30-+50	Sand	45-+50	40-45	10-25
3	-	45-+50	-	-	35-45	35-40	
4	-	40-45	25-30	-	30-35	30-35	
5	5-20	35-40	20-25	-	25-30	25-30	
6	-	20-35	-	-	-	20-25	
7	-	10-20	15-20	-	20-25	15-20	2.5-5
8	-	-	1-5; 10-15	-	15-10	10-15	5-10
9	-	-	-	Ball- type	8-15	5-10	-
10	1-5	1-10	5-10	Rocks	1-8	1-5	0-2.5

Table A.2: Weights assigned to criteria on each submodel by experts interviewed.

Species requirements submodel				Operational factors submodel			
Criterion	**Stotz, W.**	**Figueroa, M.**	**Perez, H.**	**Criterion**	**Stotz, W.**	**Figueroa, M.**	**Perez, H.**
Bathymetry[1]	15	10	10	Bathymetry[2]	35	40	25
Seabed	15	40	20	Coastline exposure[2]	35	30	40
Coastline exposure[1]	45	40	40	Accessibility by land	15	20	10
Red sea urchin natural stocks distribution	25	10	30	Accessibility by sea	15	10	25
Total (%)	**100**	**100**	**100**		**100**	**100**	**100**

Table A.3: Final weights assigned to each submodel by experts interviewed.

Submodel	**Stotz, W.**	**Figueroa, M.**	**Perez, H.**
Species requirements submodel	70	60	55
Operational factors submodel	30	40	45
Total (%)	**100**	**100**	**100**

APPENDIX 2

A.2.1 Calculation of annual size thresholds based on the individual growth function VBGF

L_t=L_{inf}*(1-EXP(-K*(t))) **[mm]** **[Equation A.1]**

, where L_t: asymptotic length (diameter) at age t, L_{inf}: limiting asymptotic length (diameter) equal to 130 mm (Stotz *et al*., 1992), K: constant growth parameter equal to 0.175 year^{-1} (Stotz *et al*., 1992), and t: age [years].

Table A.4: Annual size thresholds estimated using the VBGF.

Ageclass	L_t (mm)	Size thresholds (mm)
1	20.87	0-20.87
2	38.39	20.88-38.39
3	53.10	38.40-53.10
4	65.44	53.11-65.44
5	75.81	65.45-75.81
6	84.51	75.82-84.51
7	91.81	84.52-91.81
8	97.94	91-82-97.94
9	103.09	97.95-103.09
10	107.41	103.42-107.41
11	111.04	107.42-111.04
12	111.08	111.05-114.08+

A.2.2 Estimation of natural mortality rates for released individuals

Table A.5: Instantaneous constant natural mortality rates (M_R) estimated from various stocking experiments carried with the red sea urchin *L. albus* Chile.

Total survival (%)	Time (months)	S	M_R (year^{-1})	Annual survival (%)	Annual mortality (%)	Source
15.00	55.00	0.15	**0.414**	66.11	33.89	(Olave *et al*., 1993)
27.70	24.00	0.28	**0.642**	52.63	47.37	" "
36.21	18.00	0.36	**0.677**	50.80	49.20	" "
50.00	12.00	0.50	**0.693**	50.00	50.00	(Stotz *et al*., 1992)
51.02	10.00	0.51	**0.808**	44.60	55.40	(Bustos *et al.,* 1991)
65.33	6.00	0.65	**0.851**	42.68	57.32	" "
35.90	28.00	0.36	**0.439**	64.47	35.53	(Figueroa, 2000
Mean			**0.646**			
Standard Deviation			**0.167**			

A.2.3 Estimation of natural and fishing mortality rates for wild individuals based on the 'linearized length-converted catch curve' (Sparre and Venema, 1992)

Ln [C(L1,L2)/Delta t(L1,L2)]=c–Z*t((L1+L2)/2) **[Equation A.2]**

, this is a linear equation where: y=ln [C(L1,L2)/Delta t (L1,L2)], x= t((L1+L2)/2), and the slope b is –Z.

Table A.6: Linearized catch curve based on length composition data (extracted from the Base Line Study (del Campo *et al.,* 1999) for *L. albus* from Quintay Bay, Chile. L_{inf}: 130 mm, K: 0.175 $year^{-1}$.

A	B	C	D	E	F	G
L1-L2	**C(L1,L2)**	**t(L1)**	**Delta t**	**t((L1+L2)/2)**	**ln ((C(L1,L2)/delta t))**	**t(L1)**
0-1.8	4	0.852	0.103	0.903113325	3.659681022	0.851631881
1.8-2.0	7	0.955	0.105	1.00702088	4.201113489	0.95459477
2.0-2.2	4	1.059	0.107	1.112853085	3.622977594	1.05944699
2.2.-2.4	16	1.166	0.109	1.220682593	4.990402351	1.166259179
2.4-2.6	24	1.275	0.111	1.330586253	5.376634912	1.275106008
2.5-2.8	14	1.386	0.113	1.442645433	4.818028683	1.386066498
2.8-3.0	29	1.499	0.115	1.556946389	5.526265183	1.499224368
3.0-3.2	43	1.615	0.118	1.673580659	5.89975918	1.61466841
3.2-3.4	42	1.732	0.120	1.792645506	5.855393088	1.732492909
3.4-3.6	42	1.853	0.123	1.914244405	5.834114084	1.852798104
3.6-3.8	34	1.976	0.126	2.038487582	5.601063291	1.975690705
3.8-4.0	45	2.101	0.128	2.165492617	5.859140289	2.101284458
4.0-4.2	43	2.230	0.131	2.295385115	5.790947707	2.229700777
4.2-4.4	38	2.361	0.134	2.428299445	5.644074792	2.361069453
4.4-4.6	45	2.496	0.138	2.564379585	5.789338223	2.495529438
4.6-4.8	43	2.633	0.141	2.703780054	5.719481976	2.633229733
4.8-5.0	43	2.774	0.145	2.84666697	5.694478069	2.774330376
5.0-5.2	45	2.919	0.148	2.99321924	5.714295201	2.919003564
5.2-5.4	27	3.067	0.152	3.143629907	5.17714923	3.067434915
5.4-5.6	38	3.220	0.157	3.298107682	5.491866559	3.219824899
5.6-5.8	32	3.376	0.161	3.456878685	5.292233164	3.376390465
5.8-6.0	28	3.537	0.166	3.620188439	5.130124509	3.537366905
6.0-6.2	32	3.703	0.171	3.788304153	5.234237774	3.703009973
6.2-6.4	21	3.874	0.176	3.961517359	4.782714318	3.873598334
6.4-6.6	23	4.049	0.181	4.14014695	4.842428463	4.049436383
6.6-6.8	27	4.231	0.187	4.324542725	4.970504652	4.230857517
6.8-7.0	30	4.418	0.194	4.515089509	5.04252257	4.418227933
7.0-7.2	36	4.612	0.201	4.712211999	5.190351111	4.611951085
7.2-7.4	29	4.812	0.208	4.916380467	4.938402321	4.812472913
7.4-7.6	43	5.020	0.216	5.128117531	5.295256859	5.020288022
7.6-7.8	43	5.236	0.224	5.34800622	5.256781086	5.235947039
7.8-8.0	46	5.460	0.233	5.57669967	5.284206353	5.4600654
8.0-8.2	52	5.693	0.243	5.814932839	5.365123907	5.69333394
8.2-8.4	58	5.937	0.254	6.063536773	5.43082437	5.936531737

Portion not used; small numbers in the sample

Portion used in the regression analysis for stage 'before fishing starts'

, where the input data are the catch in numbers by length group (columns A and B), as well as the values of K and L_{inf}. Then t(L) is calculated from $t(L)=t_0-1/k*Ln(1-L/L_{inf})$; Delta t (column D) from column C, while t((L1+L2)/2)=x is derived from column C, and ln ((CL1,L2)/delta t)) (column F) from columns B and D.

Cont. Table A.6.

A	B	C	D	E	F	G
L1-L2	C(L1,L2)	t(L1)	Delta t	t((L1+L2)/2)	ln ((CL1,L2)/delta t))	t(L1)
8.4-8.6	70	6.191	0.266	6.323456139	5.573398552	6.190541809
8.6-8.8	51	6.456	0.279	6.595770939	5.209082868	6.45637047
8.8-9.0	70	6.735	0.293	6.881723677	5.475721186	6.735171408
9.0-9.2	60	7.028	0.309	7.182753722	5.268902425	7.028275947
9.2-9.4	35	7.337	0.327	7.500541251	4.674307432	7.337231497
9.4-9.6	32	7.664	0.346	7.83706421	4.525820766	7.663851005
9.6-9.8	25	8.010	0.369	8.19467319	4.216399526	8.010277415
9.8-10.0	25	8.379	0.394	8.576191454	4.149658611	8.379068965
10.0-10.2	14	8.773	0.423	8.985051008	3.498320191	8.773313944
10.2-10.4	10	9.197	0.457	9.425481522	3.084810729	9.196788071
10.4-10.6	9	9.654	0.497	9.902778906	2.895971671	9.654174972
10.6-10.8	8	10.151	0.545	10.42369764	2.687090892	10.15138284
10.8-11.0	3	10.696	0.602	10.99704248	1.606010311	10.69601244
11.2-11.4	1	11.298	0.673	11.63459549	0.395941723	11.29807253
11.4-11.6	3	11.971	0.763	12.35263671	1.369061662	11.97111845
11.6-11.8	1	12.734	0.881	13.17458549	0.126855409	12.73415498
11.8-12.0	0	13.615	1.042	14.13593474	-	13.615016
12.0-12.2	1	14.657	1.275	15.29440647	-0.243029318	14.65685347
12.2-12.4	0	15.932	1.644	16.75390826	-	15.93195948
12.4-12.6	0	17.576	2.317	18.73432877	-	17.57585704
12.6-+A23	1	19.893	-19.893	9.946400255	-	19.89280051

Portion used in the regression analysis for stage ‘under full exploitation’

Portion not used; too close to L_{inf}

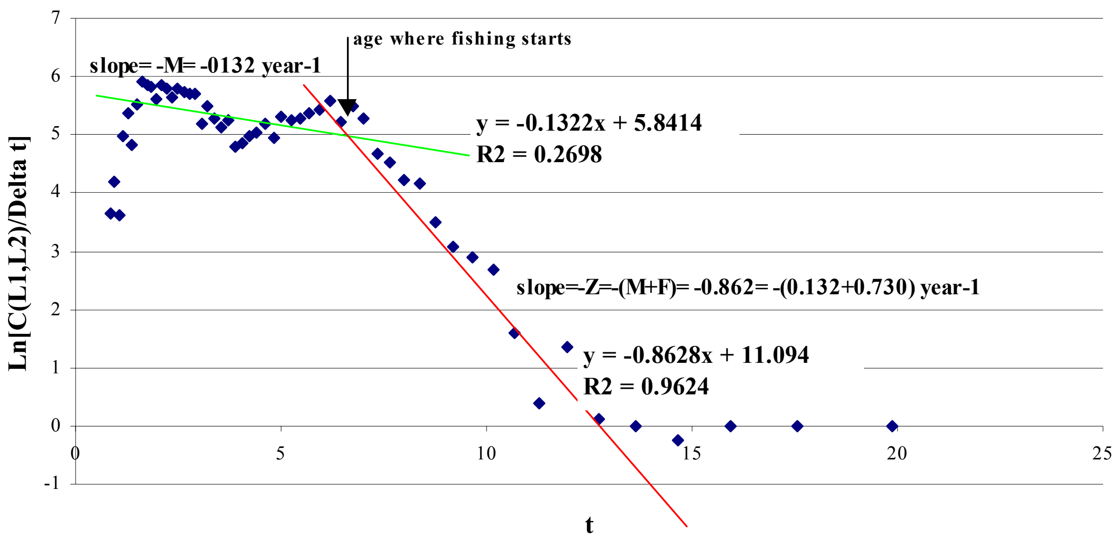


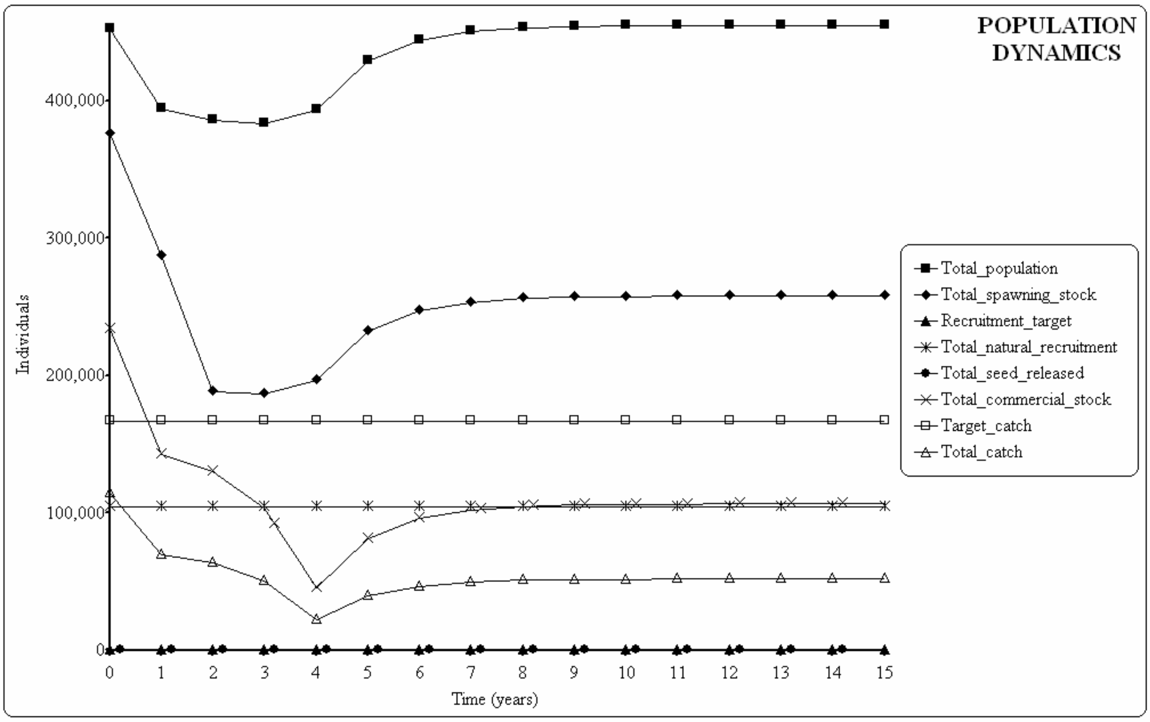
Figure A.4: Linearized catch curve based on length composition data used to estimate natural and fishing mortality rates for *L. albus* in the cove of Quintay, Chile.

A.2.4 Reproduction parameters for the red sea urchin

Table A.7: Reproduction parameter values used for the estimation of the contribution of local spawning to recruitment in the study area, derived from productive indices registered at the MRCQ (Figueroa, pers. comm.).

Parameter	Value
Sex ratio	1:1=male:female
Fecundity	between 700,000-1,500,000
Settlement index	between 15-20
Post settlement survivorship	75

A.2.5 Estimation of natural recruitment level to support the actual population structure

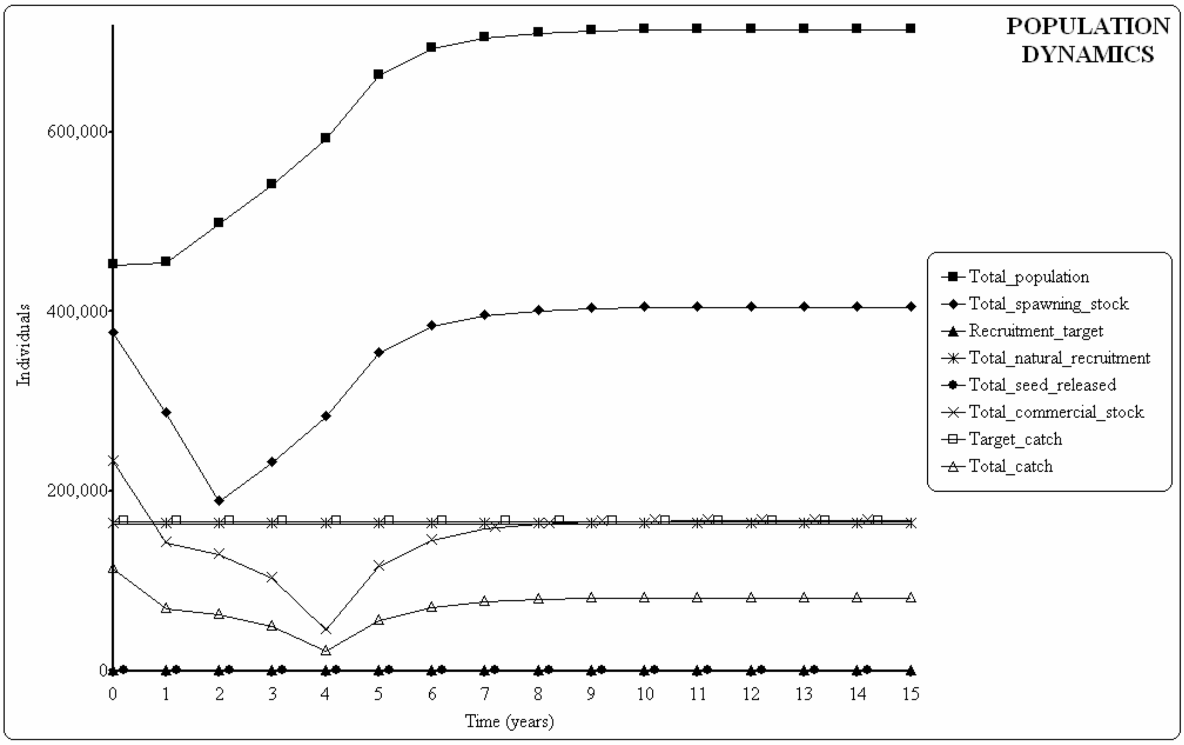


PRODUCTIVE TARGETS AND RESULTS (individuals/year)

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total_natural_recruitment	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000	105,000
Restocking_target	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total_seed_released	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	81,506	96,449	102,734	105,356	106,448	106,905	107,093	107,163	107,197	107,214	107,222
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	81,506	96,449	102,734	105,356	106,448	106,905	107,093	107,163	107,197	107,214	107,222
Total_population	452,775	395,330	386,302	384,150	394,388	429,825	444,768	451,052	453,675	454,766	455,224	455,412	455,482	455,516	455,532	455,540

Figure A.5: Population dynamics and structure based on the final estimate of 105,000 recruits/year required to support the actual population structure in the AMEBRQ.

A.2.6 Estimation of recruitment target of the system



PRODUCTIVE TARGETS AND RESULTS (individuals/year)

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target_catch	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273	167,273
Recruitment_target	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total_natural_recruitment	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000	165,000
Restocking_target	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total_seed_released	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial_stock_W	234,740	143,686	130,996	104,328	46,070	116,893	146,780	159,376	164,664	166,881	167,814	168,203	168,358	168,433	168,469	168,486
Total_commercial_stock	234,740	143,686	130,996	104,328	46,070	116,893	146,780	159,376	164,664	166,881	167,814	168,203	168,358	168,433	168,469	168,486
Total_population	452,775	455,330	498,883	542,809	593,428	664,251	694,138	706,734	712,022	714,239	715,172	715,561	715,716	715,791	715,827	715,844

Figure A.6: Population dynamics and structure based on the final estimate of target recruitment of 165,000 recruits/year required to support the commercial targets of the system.

A.2.7 Estimation of potential range of variation for natural recruitment at the study area

Methodology: Direct estimation of maximum recruitment level based on the following equation described by Morgan *et al.,* (2000) (Eq.A.3).

$TR=(TNR_A/SA)*TIA$ [individuals/year] [Equation A.3]

, where TNR_A: estimated number of recruits per sampled area [individuals/study area*year], SA: sampled area [m^2], and TIA: total inhabitable area [m^2].

Table A.8: Direct estimation of the total natural recruitment based on the density of recruits and the potential inhabitable area.

TNR_A: Number of recruits estimated (Individuals/study area*year)	Sampled area (m^2)	Inhabitable area (m^2)	Total recruitment (individuals/study area*year)
41,131	15,400	73,610	197,512
Maximum recruitment level	**≈200,000**		
Minimum recruitment level (equal to 1/8 maximum level)	**≈25,000**		

*Source of recruitment and inhabitable area data: Base Line Study (del Campo *et al.,* 1999).

A.2.8 Estimation of mean density reduction on restocked patches

Table A.9: Patch density data collected from experimental restocking exercises at Quintay (Figueroa, pers. comm.).

Size (mm)	Mean density (ind/m2)	
	20.00	1,040.00
	30.00	528.00
	40.00	384.00
	50.00	256.00

Table A.10: Estimation of the annual density reduction on restocked patches based on the experimental restocking carried out at Quintay.

Size (mm)	Mean density (ind/m2)	Change (%/year)
20.87	958.95	-59.72%
38.39	386.25	-38.37%
53.10	238.06	-26.78%
65.44	174.30	-19.71%
75.81	139.95	-14.96%
84.51	119.01	-11.63%
91.81	105.17	-9.19%
97.94	95.50	-7.36%
103.09	88.47	-5.94%
107.41	83.22	-4.84%
111.04	79.19	-3.95%
114.08	76.06	-100.00%
Range	**(3.95- 59.72)**	
Mean	**-18.40%**	

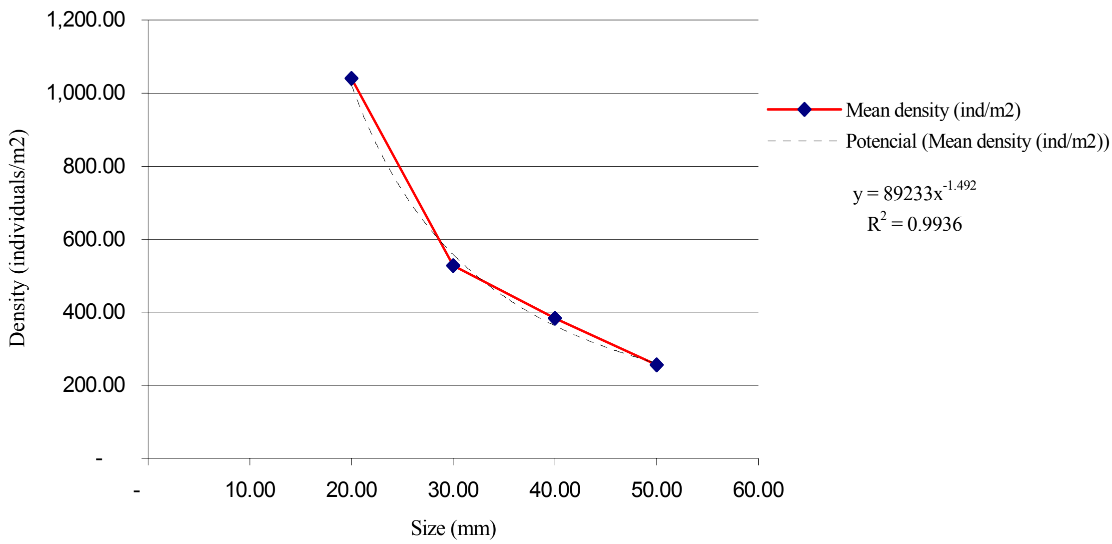


Figure A.7: Estimated density reduction on restocked patches of red sea urchin juveniles.

APPENDIX 3

Questionnaire of socio-economic characterization, fishing actvities and determination of productive requirements and expectations by local fishing population at the Cove of Quintay, V Region, Chile

The present questionnaire has the objective of providing with essential information and data to run a bio-socio-economic simulation model especially designed to support decision- making for coastal management of the red sea urchin in Chile. This work is part of a Ph.D. research project, which has been developed at the Institute of Aquaculture, Stirling University, Scotland. Your help on the completion of this inquest will be most appreciated. This information will remain entirely confidential and be utilised strictly for research purposes.

1. Family structure and educational level

Name (optional)	**Age**	**Reads**		**Education**			
		NO	YES	Primary	Secondary	High S.	Graduate

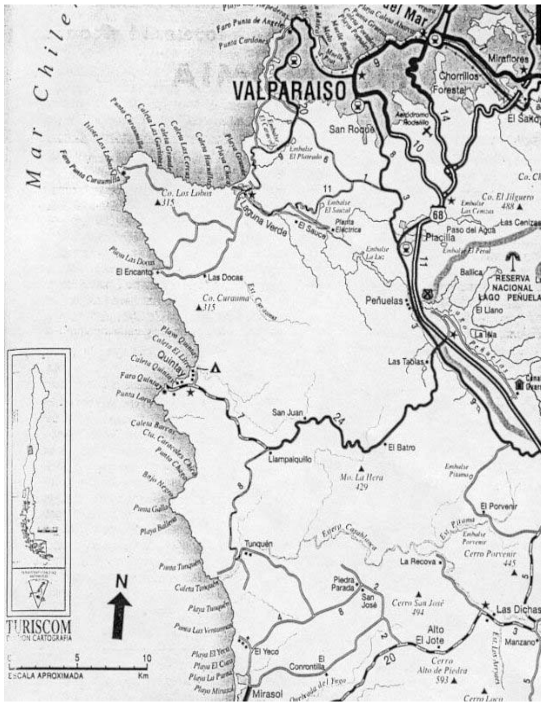
2. Employment and prioritisation of activities

Activity/ Importance	**High-principal**	**Medium-secondary**	**Low- occasional or alternative**	**Monthly earning**
Agriculture				
Livestock				
Fishing				
Aquaculture				
Individual sales				
Graduate				
Handcrafting				
Building worker				
Janitor, maiden or waitress				
Other ( )				

3. Fishing activities

Resource	**Commercial importance**	**Fishing season**	**Days per season**	**Capture per unit of effort**
	High Medium Low			
Red sea urchin	……………………………	…………………	………………	………………………..
Loco	……………………………	…………………	………………	………………………
Lapa	……………………………	…………………	………………	………………………
Other:	……………………………	………………	………………	………………………

4. Fishing operations characterisation



- Fishing ground: (Please show in the map):
- Time spent to arrive at fishing site:…………………………………….…
- What is your position in the fishing crew?

  Skipper Diver Crew

5. Post-harvest operations

- Where do you sale your catch?

Product	Co-operative	Middlemen	Broker	Other	Price
Red sea urchin					
Loco					
Lapa					
Other: ………………					
Other: ………………					
Other: ………………					
Other: ………………					

- Do you practice any kind of processing?

  Filleting CarvingGutting
- Do you select the catch to be processed? ………………………
- Do you select by size?………………………………………………

6. Fishing fleet and equipment

- Who is the owner of the equipment and fishing gears and arts?

Co-operative ( ) Fisherman ( ) Family ( ) Other (______________)

- Which is approximately the investment on fishing equipment? ___________________
- How much do you spend in equipment and fishing gears and arts maintenance? ______
- Which is the normal fishing cost per session?________________________________

7. Red sea urchin management and exploitation and the AMEBRQ

- Which is the catch of sea urchins that has been historically obtained from the AMEBRQ (‘good times’)?____
- Which is the current state of natural stocks of red sea urchins in the AMEBRQ?

  Good and stabilized ( ) Bad and recovering ( )

  Bad and declining ( ) Overexploitation ( )

  Other (please state)____

- Which percentage of your capture currently comes from the AMEBRQ and from external fishing grounds?____
- Which is the annual capture that would be desirable to obtain from the AMEBRQ?____
- Do you support the application of controlled restocking programmes and coastal management plans for the red sea urchin in the AMEBRQ?

  Yes (   )   No (   )   Why?______________________________________
- Would you support collective investment in a massive seed buying for development of restocking activities or would you rather use this money for other activities?

  Yes (   )   No (   )   Why?______________________________________
- If that would be the case (positive investment on hatchery reared seed and development of restocking activities), which would be an estimated period after which you would expect to get successful productive results?___________________________________
- In that situation, which would be an acceptable annual increase in total production of sea urchins after the implementation of the restocking programmes?_______________
- Have you ever been involved in any fisheries resource management and/or Aquaculture development programme?____

  Yes (   )   No (   )   Why?______________________________________
- Which specie?

  Red sea urchin (   )   Loco (   )   Lapa (   )

  Other (please state)____
- Do you believe- support the system of management and exploitation areas in Chile?

  Yes (   )   No ( )   Why?______________________________________
- How do you assess- evaluate this system?

Secure and stable, but small- volume source of benthic resources production (   )

Large overall catch contribution and potential unique sustainable source of production (   )

Totally inefficient and costly production and administrative system (   )

Other (please state)____

Results of the Questionnaire of socio-economic characterization and determination of productive requirements and expectations by local fishing population at the Cove of Quintay, V Region, Chile

Table A.11: Summary of the results of the sections 1 and 2 of the socio-economic and productive questionnaire.

Name	**Age (years)**	**Reads**		**Education level**				**Activity/ Importance**									
		NO	**YES**	**Primary**	**Secondary**	**High**	**Graduate**	**Agriculture**	**Livestock**	**Fishing**	**Aquaculture**	**Individual sales**	**Graduate**	**Handcrafting**	**Building worker**	**Janitor, maiden waitress**	**Other**
1	51		1	1						HP							
2	32		1	1						HP							
3	37		1	1						HP							
4	48		1	1						HP							
5	34		1	1						HP							
6	34		1	1						HP							
7	34		1	1	1					HP							
8	39		1	1						HP							Diver (MS)
9	54		1	1	1					HP							Diver (MS)
10	30		1	1						HP							
11	38		1	1						HP							Diver (MS)
12	45		1	1	1					HP							Diver (MS)
13	47		1	1	1					HP							Diver (MS)
14	50		1	1						HP							Diver (MS)
15	52		1	1						HP							
Total/Mean	**42**		**15**	**15**	**4**					**15 (H)**							**6**

Note: HP: High-principal; MS: Medium-secondary; LO: Low-occasional; ME: Monthly earning.

Table A.12: Summary of the results of the sections 3 and 4 of the socio-economic and productive questionnaire.

Resource/Commercial importance				**Fishing season (months)**			**Days per season**			**Capture per unit of effort (units/fishing session)**				
	Red sea urchin	**Loco**	**Keyhole limpet**	**Red sea urchin**	**Loco**	**Keyhole limpet**	**Red sea urchin**	**Loco**	**Keyhole limpet**	**Red sea urchin**	**Loco**	**Keyhole limpet**	**Travel tine to fishing site (minutes)**	**Position in crew**
	3	3	3	9	3	12	30		365	400			60--10 (Ext-AMEBRQ)	S, C
	2	3	3										50-60 (Ext)	C
	3	3	3										10 9 (AMEBRQ)	S
	3	3	3										25--5 (Ext-AMEBRQ)	S
	3	3	3										40-6 (Ext AMEBRQ)	D
	3	3	3	9	3	12	60	7	365	850		3000	50--15 (Ext-AMEBRQ)	D
	3	3	3	9	3	12	40	7	365	600		1000	40--10 (Ext AMEBRQ)	D
	3	3	3	5	3	8	5	5	60	1000	500	100	90 (Ext)	D
	2	2	3	9		3	6		5	1000	500	60	90 (Ext)	C
	3	3	3										30--6 (Ext AMEBRQ)	C
	3	3	3	9	3	12	34	6	16	400			25--45 (Ext)	D
	1	2	3		3	12	27	7	46	500	2200	2500	30 (Ext)	S
	3	3	3			12	27	7	144	500		2000	30--10 (Ext AMEBRQ)	D
	2	2	3		3	12	27	7	34	1000		1300	30--10 (Ext-AMEBRQ)	D
	3	3	3	9	3	12	20	7	40	300			40--5 (Ext-AMEBRQ)	D
Total	**40**	**42**	**45**	**-**	**-**	**-**	**-**	**-**	**-**					**4S, 8D, 4C**
Mean	**2.67**	**2.80**	**3.00**	**8.43**	**3.00**	**10.70**	**27.86**	**6.63**	**144.00**	**655.00± 279**	**1066.67**	**1422.86**	**46--9** (Ext-AMEBRQ)	

Note: Ext: External fishing grounds; AMEBRQ: Quintay's management and exploitation area; S: skipper, D: diver and C: crew.

Table A.13: Summary of the results of the sections 5 and 6 of the socio-economic and productive questionnaire.

Catch sale				Price					Fishing fleet and equipment			
	Red sea urchin	**Loco**	**Keyhole limpet**	**Red sea urchin ($/unit)**	**Loco ($/unit)**	**Keyhole limpet ($/Kg)**	**Size selection**	**Final market**	**Owner**	**Fleet investment ($/boat)**	**Monthly maintenance cost ($/month)**	**Fishing cost per session ($/day)**
	M	B	B	250	700	900	1	EXP.	P	4,000,000	10,000	8,100
	M	M	B	250	750	900	1	LC.	P	6,000,000	25,000	12,500
	M	M, B	B	250	750	900	1	EXP.	P	5,000,000	5,000	10,000
	-	-	-	-	-	-		LC.	P	4,000,000	35,000	35,000
	M	B	B				1	EXP.	P	4,500,000	20,000	15,000
	M	B	B	250	700	900	1	EXP.	P	4,000,000	40,000	23,000
	M	B	B	250	700	900	1	EXP.	P	5,000,000	13,000	20,000
	B	B	B	250	700	900	1	EXP.	F	4,000,000	20,000	20,000
	B	B	B	250	700	900	1	EXP.	F	4,000,000	15,000	20,000
	B	B	B				1	EXP.	P	2,000,000	10,000	10,000
	-	B	O				1	EXP.	P	5,400,000	5,000	16,000
	M	B	B	250	700	900			F	5,000,000	15,000	15,000
	M	B	B	250	700	900	1	EXP.	P	1,500,000	5,000	10,000
	B	B	B	250	700	900	1	EXP.	P	4,000,000	40,000	20,000
	M	B	B	250	700	900	1	EXP.	P	4,000,000	12,000	16,000
Total	**9M, 4B**	**2M, 13B**	**13B, 1O**	**-**	**-**	**-**	**13**	**12EXP, 2LC**	**12 P, 3 F**	**-**	**-**	**-**
Mean				**250.00**	**709.09**	**900**				**4,160,000**	**18,000**	**16,707**

Note: M: middleman, B: broker, O: other; EXP: exportation industry, LC: local consumption.

Table A.14: Summary of the results of the section 7 of the socio-economic and productive questionnaire.

Red sea urchin management and exploitation at the AMEBRQ									Participation on management programmes					
	Historical catch from the AMEBRQ (units/fishing session)	**Current state of natural stocks in the AMEBRQ**	**Catch fraction extracted at AMEBRQ (%)**	**Desirable annual catch (units/year)**	**Support restocking and management**	**Investment on seed buying**	**Minimum time expected for productive results (years)**	**Annual increase (%)**	**Red sea urchin**	**Loco**	**Keyhole limpet**	**Other**	**Support system AMEBR**	**Assessment system AMEBR**
	1,000	GS	0	180,000	Y	Y	2	80	Y	Y	Y	Y	Y	SS
	-	GS	40	100,000	Y	Y	4	100	Y	Y	Y	Y	Y	-
	-	GS	0	-	Y	Y	4	80	Y	Y	Y	Y	Y	-
	1,000	GS	0	21,000	Y	Y	4 ½	100	Y	Y	Y	Y	Y	SS
	1,000	GS	0	50,000	Y	Y	6	60	Y	Y	Y	Y	Y	SS
	1,000	GS	0	180,000	Y	Y	5	60	Y	Y	Y	Y	Y	SS
	1,000	GS	0	40,000	-	Y	5	70	Y	Y	Y	-	Y	SS
	2,000	BR	0	150,000	Y	Y	5	100	Y	Y	Y	-	Y	SS/LOCC
	2,000	BR	0	150,000	Y	Y	4	100	Y	Y	Y	-	Y	SS/LOCC
	1,000	BR	0	50,000	Y	Y	5	60				-	Y	SS
	-	BR	0	-	Y	Y	4	-	Y	Y	Y	-	Y	
	-	GS	10	27,000	Y	Y	3 ½	70	Y	Y	Y	Y	Y	LOCC
	1,000	GS	0	81,000	Y	Y	2	100	Y	Y	Y	Y	Y	SS
	1,000	GS	0	135,000	Y	Y	4 ½	80	Y	Y	Y	Y	Y	SS
	1,000	GS	0	48,000	1	Y	4 ½	70	Y	Y	Y	Y	Y	LOCC
Total	**1,182**	**11GS, 4BR**			**14Y**	**15Y**	**-**	**-**	**14**	**14**	**14**	**10Y**	**15Y**	**8SS, 4LOCC**
Mean			**3.33%**	**93,231**			**4.20**	**81**						
	Estimated	**Annual**	**Income ($/year)**	**23,307,692**										

Note: GSS: good and stabilised, BR: bad and recovering; Y: yes, N: no; SS: secure and stable catch source; LOC: large overall catch contribution.

APPENDIX 4

A.3.1 Single-variable optimisation analysis of natural mortality and cost of restocking material

Table A.15: Final results of single-variable optimisation analysis of natural mortality of released individuals towards making stocking economically viable.

Time (year)	Mr ($year^{-1}$)	Payment of Released stock ($/year)
0	0.142	-1,560,000
1	0.142	-2,015,076
2	0.142	-2,355,545
3	0.142	-2,605,538
4	0.142	-2,770,491
5	0.142	571,619
6	0.142	1,712,823
7	0.142	2,187,635
8	0.142	2,387,886
9	0.142	2,474,846
10	0.142	2,519,584
11	0.142	2,577,880
12	0.142	2,563,422
13	0.142	2,545,757
14	0.142	2,529,524
15	0.142	2,515,492

***Optimisation target→** to obtain a positive value for released stock-specific payment from year 5 onwards (when released individuals incorporate to harvestable stock), based on limiting recruitment level.

Table A.16: Final results of single-variable optimisation analysis of the average unit cost of restocking material towards making stocking economically viable.

Time (year)	Unit seed price ($/individual)	Restocking costs ($/year)
0	17.0	2,251,843
1	17.0	2,251,843
2	17.0	2,251,843
3	17.0	2,251,843
4	17.0	2,251,843
5	17.0	2,251,843
6	17.0	2,251,843
7	17.0	2,251,843
8	17.0	2,251,843
9	17.0	2,251,843
10	17.0	2,251,843
11	17.0	2,251,843
12	17.0	2,251,843
13	17.0	2,251,843
14	17.0	2,251,843
15	17.0	2,251,843

***Optimisation target→** to obtain a cost reduction, allowing stocking costs to be covered by incomes generated from harvesting stocked individuals (gross incomes≈2,500,000 $/year, when released individuals incorporate to harvestable stock), based on limiting recruitment level.