António Augusto Mousinho Almadanim Santa Marta

Degree in Environmental Engineering Sciences

Sustainable Aquaculture in Saldanha Bay, South Africa

Dissertation submitted to obtain the degree of Master in
Environmental Management Systems
Thesis advisor: João Gomes Ferreira FCT-UNL

Jury:

President: João Gomes Ferreira
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ABSTRACT

Saldanha Bay, located near the coastal town of Saldanha, in Western Cape Province of South Africa, possesses excellent conditions for mussel and oyster aquaculture. Its linkage with the adjacent upwelling current system provides a very productive environment for phytoplankton growth, and this has led to the development of a vibrant shellfish aquaculture industry. The main objectives of this work are to develop a model which simulates the main ecological processes within the Bay, to determine the Bay's carrying capacity for mussel and oyster production, and to produce a management tool for decision making.

Bivalve aquaculture has great growth potential and may be important for human food security as mankind faces a projected need of an additional 30 X 10^6 tonnes per year of aquatic products by 2050. Bivalve aquaculture is organically extractive, and can additionally provide significant ecosystem services in top-down control of eutrophication, and creation of structure for stimulating biodiversity. When managed properly, this form of aquaculture has a very low environmental footprint, mainly associated with organic enrichment of the sediment. This impact is even less relevant in upwelling systems such as Saldanha Bay where particles tend to be flushed out in the surface layer, and in all cases it must be borne in mind that by definition shellfish aquaculture results in a net removal of seston from the water column.

This model was developed using EcoWin an object oriented approach to ecological modelling. The model for Saldanha Bay was set up using oceanographic and water quality data collected from Saldanha Bay, and culture practice information provided by local shellfish farmers. The first step was the construction and calibration of the ecological model, in order to provide a general description of the biogeochemical behaviour of the Bay, followed by the addition of the shellfish aquaculture component.

EcoWin successfully reproduced the key ecological processes, correctly simulating a mean phytoplankton biomass of 7.5 chl *a* L^{-1}. The aquaculture module simulated an annual harvested biomass of about 3000 t y^{-1}, in good agreement with reported yield.

Six production scenarios were explored, for illustrative purposes:

- Increase in stocking density of shellfish
- Two alternatives for aquaculture development in particular areas of Saldanha Bay
- Prediction of the maximum production capacity of the Bay.

These results were analysed in terms of their impacts and potential.

This study demonstrates the relevance of aquaculture-oriented ecological models in evaluating different stakeholder-defined development scenarios, and their utility in avoiding the social and environmental impacts of testing different scenarios *in situ*. The present application of EcoWin shows great potential for supporting both water managers and industry in Saldanha Bay.

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1 Introduction

The government of South Africa approved a National Development Plan, Vision 2030 that aims to reduce poverty, unemployment and inequality by this date. For the present government, “aquaculture’s role and contribution to food security is central to addressing poverty, unemployment, and inequality” (National Aquaculture Policy Framework, 2013).

The coastal Town of Saldanha, in South Africa, is located near a Bay which has excellent conditions for mussel and oyster culture. This Bay is home for farms of both species, with an annual total production of about 2400 tonnes. Saldanha Bay is located in the southwest coast of the country, forming part of the Benguela Current Large Marine Ecosystem. Due to the upwelling in Benguela current system, this Bay has nutrient rich waters, providing a productive environment for phytoplankton growth (Olivier et al., 2013).

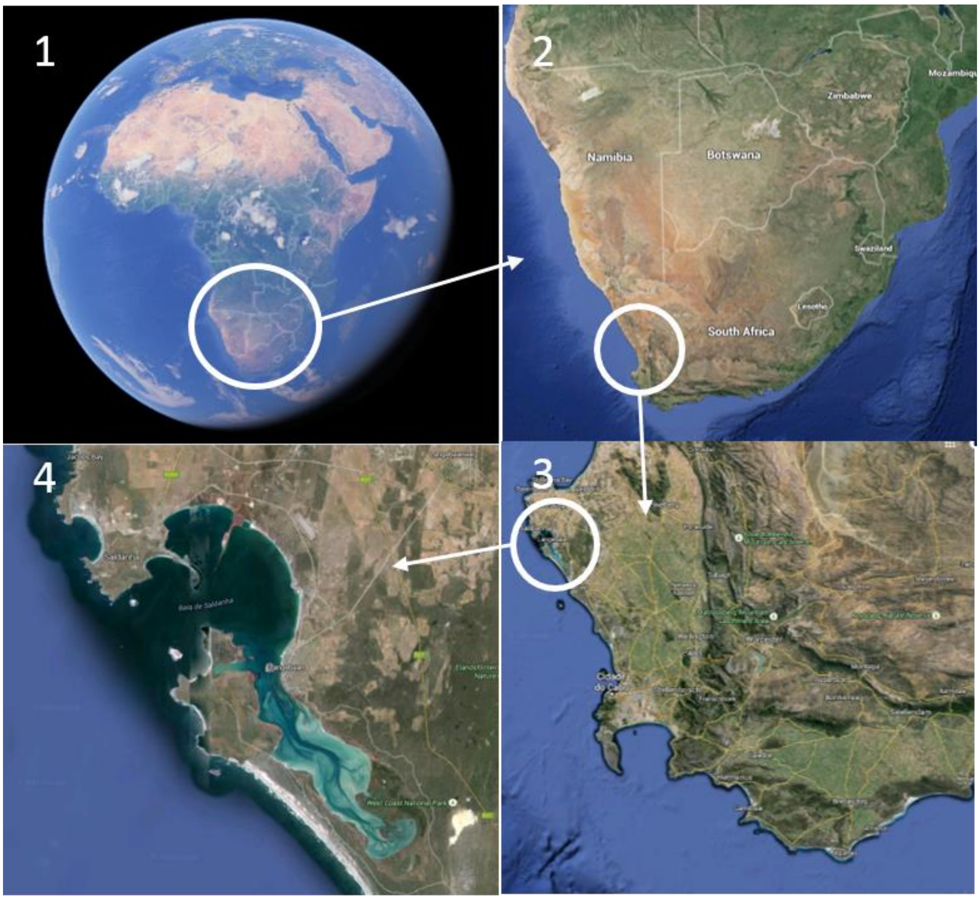


Figure 1 – Location of Saldanha Bay: 1) Southern Africa; 2) South Africa; 3) North from Cape town; 4) Satellite view of Saldanha Bay.

The central question addressed in this thesis is whether the current farming activities are working at the Bay's carrying capacity defined as the maximum production achievable without affecting the ecosystem, including other such as fisheries to an unacceptable level. This question is developed into four main objectives: (1) to analyse the carrying capacity of Saldanha Bay for shellfish production at the scale of the Bay; (2) to describe the main environmental variables and processes and their interactions with the aquaculture activities; (3) to develop different production scenarios; (4) to illustrate how ecological models can support management decisions for Saldanha Bay.

1.1 Carrying capacity

Carrying capacity has been interpreted in a range of different perspectives, such as, physical, social, economic and environmental. Davies and McLeod (2003), for instance, considered bivalve carrying capacity as "the potential maximum production a species or population can maintain in relation to available food resources" (production perspective) as Lindsay G. Ross et al. (2013) defined carrying capacity as "the level of resource use (…) that can be sustained over the long term by the natural regenerative power of the environment" (an ecological perspective). Inglis, G.J. et al. (2000) defined carrying capacity in the broader and more important perspective, considering that carrying capacity can be interpreted in four categories: physical, production, ecological and social carrying capacity;

With a similar perspective, FAO defined in 2013 an approach to aquaculture, which has three principles: (1) aquaculture development without degradation of the ecosystem beyond its resilience capacity; (2) improvement of human well-being and equity for all relevant stakeholders; and (3) development in the context of other policies, sectors, and goals.

Physical carrying capacity concept defines an area, available and physically suitable for a certain type of aquaculture. This concept depends on the match on needs of the target species and the characteristic of the selected area, and uses characteristics such as depth, temperature, salinity, and substrate type. Production carrying capacity is the optimization of the production level for the target species (marketable cohort within a specific time-frame). This is mainly dependent on natural processes, e.g. primary production and hydrodynamics. Ecological carrying capacity is the maximum production that can be accomplished without having an unacceptable environmental impact. Social carrying capacity is the level of production that causes unacceptable social impacts. It comprises the trade-offs between stakeholders in order to meet the demands of population and environment (McKindsey et al., 2006).

The individual use of either ecological or production carrying capacity criteria is not adequate for shellfish farming management. The strict ecological perspective does not allow any change in the receiving environment and the production capacity does not consider any environmental criterion (Guyondet et al., 2010). A general carrying capacity should be a compromise between production and ecological carrying capacity (Gibbs, 2007; McKindsey et al., 2006), the ultimate goal must be the development of the most productive farm without compromising its long term viability nor the ecosystem stability (Guyondet et al., 2010). McKindsey et al. (2006), uses the definition of G.J. et al. (2000) to build a decision framework that integrates its four categories to determine the overall capacity for bivalve aquaculture. This framework uses physical carrying capacity, production carrying capacity, ecological carrying capacity and social carrying capacity, in this order. In this way it is possible to calculate the general carrying capacity for a certain location. This study intends to combine physical, production, and ecological carrying capacity concepts, using these methods. The generic carrying capacity should also include both local and system scale approaches (Smaal et al., 1997). The system scale is used to determine the propagation of local effects (Guyondet et al., 2010) and the local scale is used for farm management considerations (Ferreira et al., 2007; Strohmeier et al., 2008).

The importance given to sustainable development and consequently to ecological carrying capacity varies around the globe, for instance, the developing and underdeveloped countries are less committed to it (Aguilar-Manjarrez et al., 2010). Carrying capacity is a central concept in ecosystem-based management, as it avoids “unacceptable changes” in the natural ecosystem and social structures by setting upper limits to aquaculture considering environmental limits and social acceptability for aquaculture. It is very important to evaluate the carrying capacity to an area before establish large-scale shellfish farms, to ensure a suitable food supply for the expected production and to avoid and minimize ecological impacts (Ferreira et al., 2008).

1.2 Aquaculture potential

In 2050 the Human population should reach 9700 million people (United Nations, 2015), which is above the earth’s estimated maximum carrying capacity (Cohen, 1995). A very important question to science is whether it is possible to increase food production to fulfil the human needs for such a large number of people. The present population is already under water stress and global warming worsens this situation. Agriculture production to 9700 million people demands bigger water resources and the rise of agricultural production for non-food supplies augments the problem. On the top of this, global fisheries landings have been declining. Under these circumstances mariculture, the least fresh water dependent food producer, might have an important role feeding mankind in the future. (Duarte et al., 2009).

Fish have the highest protein content in their flesh of all food animals. They are more efficient than any terrestrial farmed animals, converting feed to body tissue. Besides all this, aquatic animals discharge two to three times less nitrogen to the environment when compared to terrestrial food production systems (Costa-Pierce, 2010).

1.3 Aquaculture

Aquaculture is the cultivation of aquatic organisms including finfish, shellfish, and plants. Cultivation involves the enhancement of natural production processes such as feeding, stocking, and protection from predators. The act of farming means that there is some kind of ownership, individual or corporate, over the stock (Handbook of Fishery Statistical Standards.).

Aquaculture can take place on land or in waterbodies; the latter include freshwater such as rivers or lakes, brackish water such as estuaries, and fully saline water such as Bays and open coastal water. In onshore aquaculture, ponds are most widely used for production. Cage based aquaculture for freshwater has bigger impacts. Although the use of ponds in brackish water faces substantial competition for space and environmental problems, ocean onshore production has developed in some areas where it wouldn't be possible otherwise. The coastal floating cage farms have proved to be the most effective production system. The production of seaweed and marine molluscs has been developing since the 1990s to specialized techniques allowing it to grow significantly. (Bostock et al., 2010)

Growth of freshwater aquaculture is increasing pressures on natural resources, mainly water, feeds, and energy. Most freshwater aquaculture involves water intake from the environment and post-production effluent stream. Given the increasing pressures on fresh water supplies greater use of brackish and marine water is expected in the future (Bostock et al., 2010).

Aquaculture in coastal waters can have serious environmental problems as well. Shrimp farming, for instance, may cause serious environmental impacts. Marine cage finfish aquaculture can have impacts on biodiversity and the ecosystem, in bigger scales it can have impacts in the sediments beneath the cages, release of nutrient, or chemical wastes, or the escape or release of fish with diseases. The most immediate problem, however, is with competition for uses, such as boating and navigation, recreation, preservation of seascape and tourism. (Bostock et al., 2010)

Most mollusc farming needs no feed inputs and the majority of freshwater fish production uses a low-protein, grain-based diets, and organic fertilizers. Much of the marine species crustaceans and other fish aquaculture use a higher quality diet usually containing fish meal and fish oil. Some aquaculture, such as tuna fattening needs small pelagic fishes. Although not essential, feeds for herbivorous and omnivorous species frequently contains fish meal and oil. The rapid expansion of carnivorous species could also increase pressure on fish meal and oil supplies. Overall the supplies of fish meal and oil won't be sufficient to meet the increasing demands for aquafeed ingredients. Nevertheless this isn't expected to be a great constraint, but the demand for alternative feed materials will increase. (Bostock et al., 2010)

There are several approaches to integrate aquaculture with other activities, such as, fisheries, agriculture, and Integrated Multi-Trophic Aquaculture (IMTA). Many aquaculture systems need captured fish for its feeds and aquaculture has an important role in fisheries capture enhancements, releasing farmed fish. Their release can however represent significant ecological and genetic risk to wild fish stocks.

The integration of fish species from different trophic levels can be made in the same water body or with some other water based linkage. This combination generates a synergetic relationship that acts as a bioremediation measure. A perfect system of this nature would be environmentally neutral. Such methods face a number of challenges, such as species selection, economic value, and existing regulations for aquaculture.

The integration of aquaculture and agriculture is most common in developing countries, as it diminishes the risks of mono culture. These systems use the synergy between systems to diversify production and to enhance productivity.

1.4 Aquaculture around the world

The aquaculture sector has expanded strongly over the past 6 years, from 47 million tonnes in 2000, to around 64 million tonnes in 2011 in 2008 aquaculture was responsible for about 37% of the world's fish food supply. However, Asia accounts from 89% of the world production. Therefore the world does not have a massive development of aquaculture outside China. Outside China aquaculture contributes only for 23% of world fish products. It is also important to mention, that in 2008 freshwater fish represented about 60% the aquaculture production.

With few exceptions such as Norway, aquaculture development in developed countries is very limited. In these countries aquaculture growth has been limited by user conflicts, access to sites, complicated regulatory regimes, lack of government investment, consumer disinterest, and lack of aquaculture education. In the poorest nations, aquaculture development has not occurred significantly, except for, Bangladesh, India, Vietnam, and Egypt (Costa-Pierce, 2010).

1.5 Importance of site selection for Aquaculture in Africa

With the decline of fish stocks worldwide, aquaculture is looked at as an important solution, especially for Africa, in which many areas contain an undernourished population dependent on marine and freshwater fishing for incomes (Wit, 2013). The development of aquaculture needs to be planned in order to diminish environmental and social impacts, and to predict optimum production scenarios (Byron and Costa-Pierce, 2013). The use of GIS is the most efficient, cheap, and fast way to select sites for aquaculture. It involves the identification of economically, socially, and environmentally available areas (McLeod et al., 2002). The use of these models requires regional data and the costs of data collecting in the sea are often high. Given the economic panorama in most of the African countries, this kind of expenses can be a limiting factor. Therefore, use of remote sensing has great potential and importance to the use of GIS and in this region, to determine the viability of some projects and decision making (Wit, 2013).

1.6 Shellfish aquaculture

Non fed aquaculture such as the production of shellfish has different concerns than fed aquaculture. Filter feeding shellfish do not need artificial food, consuming mostly microalgae and other suspended organic materials, making them an especially attractive form of aquaculture. This type of aquaculture provides vital social and ecological services, such as nutrient removal and habitat enhancement (Costa-Pierce, 2010; Brigolin et al., 2009). They reduce water turbidity which may improve the condition of submerged aquatic vegetation (SAV), remove N from eutrophied systems by incorporating a proportion of it in tissues, and help to control or prevent harmful algal blooms. Public health standards for aquaculture demand clean waters, requiring increased water quality monitoring at farm sites. Shellfish are farmed in well-defined areas, in structures that may provide a protection or habitat for other species.

Bivalves may have an important role in the nutrient credit programs. There is an excess of nutrient inputs to the water in numerous areas of the European Union (EU) and North America, mostly from non-point sources. The concept of a nutrient credit program is to reduce the nutrient loads by using a market based approach. This approach uses economic incentives to reduce nutrient discharges, by attributing credits to the involved polluters, which they can sell if come to reduce their emissions. In this way, the ones who can reduce their emissions by a lower price can sell their remaining credits. This could create new monetary income opportunities for farmers, who can remove nutrients from the water at a low price, as table 1 shows. The shellfish nutrient removal is one of the cheapest methods of doing it as it has great potential. These programs are already in use in some parts of the US, although not in the EU nor African countries, such as South Africa.

Table 1- Nitrogen removal costs for different removal strategies, source:(Ferreira and Bricker, 2015)

Non-point-source nutrient management strategy	**Cost (euro kg^{-1} N)**
Shellfish	11 – 278
Agricultural	0.2 – 870
Urban stormwater	56 – 6720
Wastewater treatment upgrades	0.9 – 14 093
Wetlands	1.1 – 396
Other	5.2 – 404

1.6.1 Impacts of Shellfish aquaculture

Despite the benefits of shellfish aquaculture, it may accelerate the deposition of suspended materials through the production of faeces and pseudofaeces (Chamberlain et al., 2001). These animals filter suspended material from the water, digest it, and reject a portion of it as compact faeces. It is also common that bivalves reject a part of the filtered material before its ingestion, in a less compact mass called pseudofaeces (Haven and Morales-Alamo, 1972). Both these particles, settle much faster than particles of smaller grain size. Such consolidated particles are termed biodeposits. (Haven and Morales-Alamo, 1966).

Many studies have been made to determine the impacts of bivalve farming. The biodepositon process results in the enrichment of organic materials in sediment and this may cause the reduction of the level of dissolved oxygen in the lowest layer, increase levels of sulphides, changes of benthic assemblages and azoic conditions (Zhang et al., 2009), resulting in the appearance of opportunistic species and biodiversity decrease in the substrate (Stenton-dozey et al., 1999). When close to the production carrying capacity, shellfish aquaculture may reduce the zooplankton availability, by over-compete it in phytoplankton consumption. This might reduce some higher trophic level fish, which would depend on zooplankton (Jiang and Gibbs, 2005), the introduction of exotic species and proliferation of certain species such as starfish and jellyfish are possible impacts as well (McKindsey et al., 2011).

Souchu et al. (2001) tested the effects of shellfish farming in the water column in Thau Lagoon in Mediterranean France. A nutrient surplus was observed in the water column near the farms, as a cause of plankton removal by shellfish. Thau Lagoon however, has very different physical conditions than Saldanha Bay, as a Mediterranean lagoon with low tides, wind, and wave events. Chamberlain et al. (2001), studied the effects of mussel farming on the surrounding sediments in Southwest Ireland in two different farms, and obtained different results for each. One (lower current speed) showed organic material enrichment and an impoverished benthic community as the other showed no significant impacts. Studies on suspended shellfish (mussels and oysters) culture in Tasmania (Crawford et al., 2003), and Nova Scotia (Grant et al., 1995) found little impact on the benthic community. Stenton-Dozey et al. (2001) studied the impacts of mussel farms in Saldanha Bay and found significant impacts on the substrate, such as anoxic conditions, presence of opportunistic polychaetes and a significant reduction in macrofaunal biomass. Zhang et al. (2009) studied the impacts of intensive shellfish and seaweed farming in Sanggou Bay, China and found some biochemical and biological changes, but these were considered low impact over a longer term. Kaspar et al. (1985) studied the impacts of mussel production in Kenepuru Sound, New Zealand and it found a strongly affected benthic community, with biodiversity reduction and a surplus of nitrogen in the water column.

The effects of shellfish biodeposition may or may not be significant, as the examples show. This depends greatly on the dispersion of biodeposits, which is dependent on water depth, current velocity and on settling speed. The farm’s production intensity, scale, and methods are also very important as it will affect the biodeposit input (Chamberlain et al., 2001; Zhang et al., 2009). The use of methods such IMTA may help reduce the impacts and make the production more sustainable. Zhang et al. (2009) showed how shellfish and seaweed IMTA could be more sustainable, as the seaweed produced oxygen that helped to meet benthic demand and avoid anoxic conditions.

1.7 Production methods

The main cultivated species in Saldanha Bay are the oyster *Crassostrea gigas* and the mussel *Mytilus galloprovincialis*, and constitute the focus of this study the two species are cultivated using similar techniques: raft culture; long-line culture; rack culture; on-bottom culture; and perforated plastic trays/mash bags. There are several variations of the same methods with different materials. Figure 2 illustrates some of these methods.

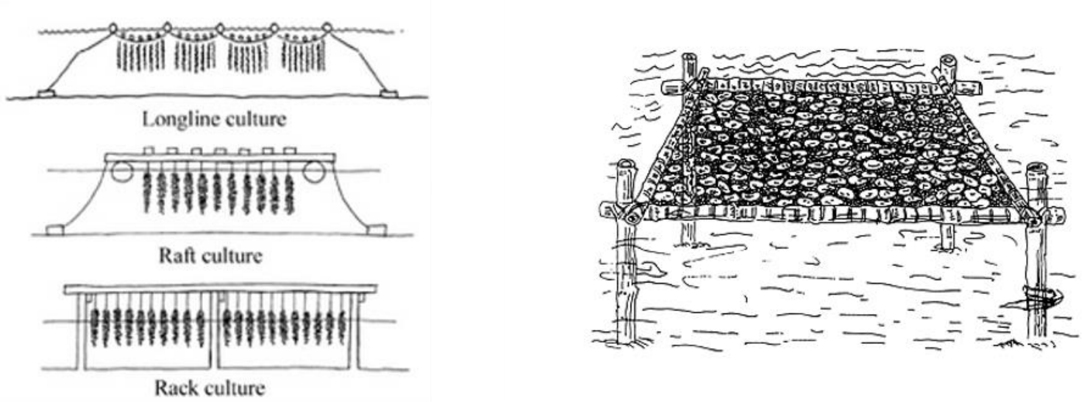


Figure 2 – Production methods illustration (left side) a tray method (right side); source: A. Figueras (2004).

Mussel seed can be collected manually or using collecting ropes where it attaches naturally, hatchery is not common for mussels. The mussels are afterwards grown on ropes, which can be suspended from rafts, wooden frames, or longlines of floating plastic buoys. Mussel can be harvested around the year, but this should be avoided during spawning periods.

Oyster seeds can be obtained through artificial collectors too or in hatcheries, which can force the animal spawning, having seeds available all year round. The oysters can be set in mesh bags or perforated plastic trays in the low intertidal zone, or in suspension ropes as with *Mytilus galloprovincialis*. They are also not harvested during the spawning period, for lower quality meat. (Aypa, n.d.; Garrido-Handog, n.d.)

1.8 Oyster and Mussel biology

The phylum *Mollusca* is of great importance in the animal kingdom as it is one of the largest and most diverse groups. Molluscs are soft-bodied animals, but most include a hard protective shell. Most molluscs have a basic body plan inside the shell, which includes a heavy fold tissue named the mantle and a large muscular foot. The mantle encloses all the interior organs and the foot is generally used for locomotion.

The class *Bivalvia* is one of six Mollusc classes and includes all the animals enclosed in two shell valves, such as, the mussel, oyster, clam, and scallops. The shell serves as protection for predators, a skeleton for the attachment of muscles, and it helps to avoid mud and sand into the mantle cavity in burrowing species. Between bivalve species the shell's form, colour, and markings diverge significantly.

Bivalves are filer feeders and feed mainly on phytoplankton, they have the ability to select the food filtered from the water. The food is bounded with mucous, passed to the mouth, and sometimes rejected and discarded out of the animal, when is named "pseudofaeces" (Helm et al., 2004).

1.8.1 Mussels

Mussels have two shells, similar in size and approximately triangular. Shell colour varies with age and location of the animal. The two shells are held and articulated together at the anterior through a ligament. The foot serves to attach the mussel to the substrate or other mussels, by the secretion of tough filaments in the ventral part of the mussel (Gosling, 2008).

Mussel length varies under the environmental conditions over which it lives. Under optimal conditions a mussel can reach a much bigger length than when exposed to marginal conditions. The shells of closely packed mussels have higher length to height ratios, from those in less crowded sites (Gosling, 2008).

The mussel species used for this study is *Mytilus galloprovincialis*, or Mediterranean mussel. These species live in waters with temperature ranging from 10 to 20°C, salinity around 34‰ psu. This species can reach up to 15cm but the normal length is 5-8cm. (Figueras, 2004). Figure 3 illustrates this species shell.

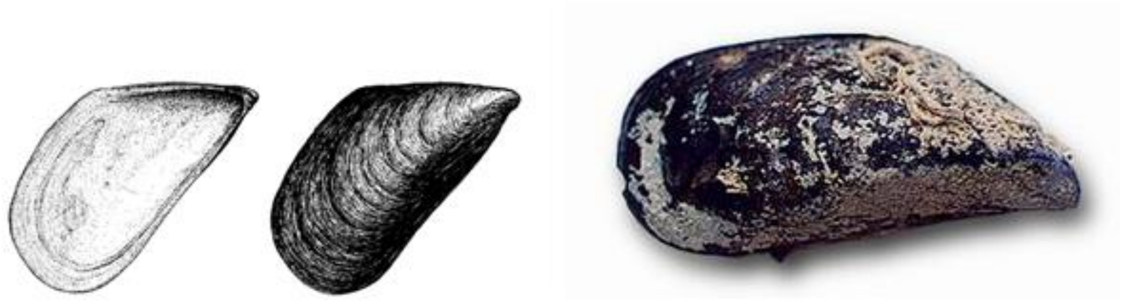


Figure 3 –Mytilus Galloprovincialis, shell illustration (left side) and picture (right side). Source: A. Figueras, (2004)

1.8.2 Oyster

The European flat oyster, *Ostrea edulis*, valves are roughly circular, one valve is flat and the other cupped, and they are hinged together by a tense ligament on the dorsal side. The flat side of the shell is attached to the substrate. The American Eastern oyster, *Crassostrea virginica,* has a more lengthened shape than the European one, and the upper shell more profoundly cupped. The shell is for both species thick and solid. In general the *Ostrea edulis* has a maximum shell height of 100mm as *Crassostrea virginica* ca reach 350mm length (Gosling, 2008).

The species studied in this work is *Crassostrea gigas,* also known as the Pacific oyster, originally from Japan. This bivalve is an estuarine species that prefers hard bottom substrate, from the lower intertidal area to depths of 40m. The optimal salinity range is 20 – 25 ‰, but it can live in salinities between 10‰ psu and 35‰ psu. It tolerates temperatures from -1.8 to 35°C and it can achieve commercial size in 18-30 months when in good conditions. Its rapid growth and wide range of tolerance to environmental conditions, made this oyster the preferred choice for many farmers worldwide. This oyster has an elongated, cupped, and extremely rough shell, as Figure 4 illustrates. The maximum length is 30 cm, but the normal length ranges between 8 to 15 cm (Helm, 2005; Pauley et al., 1988).

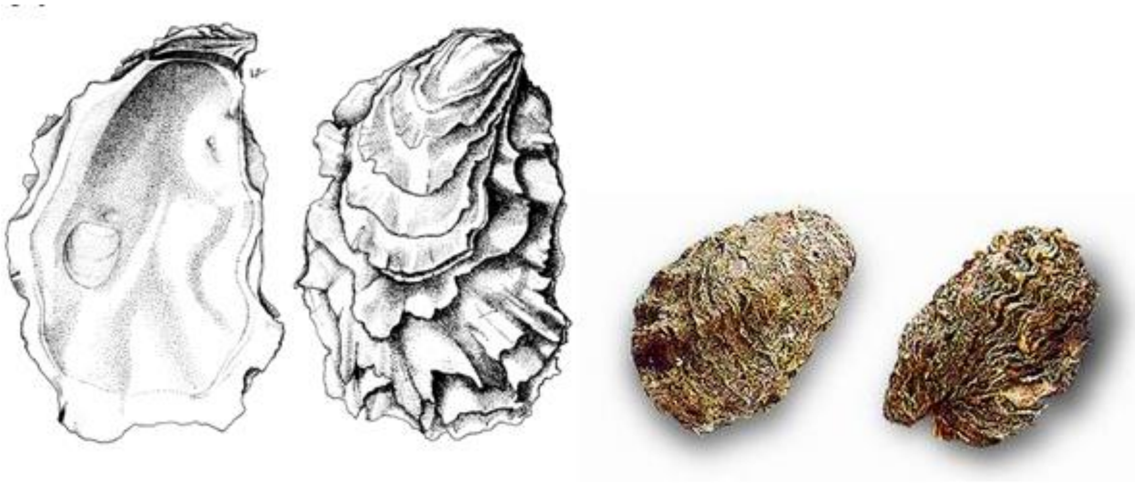


Figure 4 – Crassostrea gigas shell illustration (left side) and picture (right side). Source: (Helm, 2005)

1.9 Legal Framework

In an ideal scenario, governments regulate processes and the import export linked to mariculture, in order to protect the sector from user conflicts, overexpansion, and biosecurity risks. The state should also make policies to promote sustainable development and local participation. It may also supply investigation funding, sponsor the industry development, or provide operational loans (Britz et al., 2009).

The most relevant legislation in South Africa consists of three acts: (i) the Marine Living Resources Act of 1998, was written for fisheries and is under revision to improve its applicability for aquaculture; (ii) the National Environmental Management: Biodiversity Act of 2004, regulates farming of non -native species; (iii) the National Environmental Management: Integrated Coastal Management Act of 2008, with focuses on a sustainable management of coastal waters; (Olivier et al., 2013)

1.9.1 Health and safety regulation

Oyster are often consumed live and raw, and mussels easily accumulate algal biotoxins (Pitcher et al., 2011). Therefore, health and hygiene standards for culture, packaging, and sale are very important for consumer safety. The South African Live Molluscan Shellfish Monitoring and Control Program carries out regular and compulsory monitoring for heavy metals, biotoxins, and human microbial pathogens.

1.9.2 General policy

The most pertinent national policies to aquaculture are: the Policy for the Development of a Sustainable Marine Aquaculture Sector in South Africa (PDSMAS), from the Department of Environmental Affairs and Tourism in 2007; the National Industrial Policy Framework (NIPF); the Western Cape Aquaculture Development Initiative; and Generic Environmental Best Practice Guideline for Aquaculture Development and Operation in the Western Cape; South Africa has policies towards the development of sustainable and competitive aquaculture, the co-ordination between the different state Departments involved (PDSMAS) and towards financial and technical support to small, medium, and micro enterprises (NIPF). (Olivier et al., 2013)

Olivier et al., (2013) carried out a series of interviews with directors of all bivalve marine farms in Saldanha Bay who stated that the aquaculture sector is over-regulated. The producers in South Africa are required to obtain five permits: Mariculture permit; Fishing vessel permit (for each vessel used); Fish Processing Establishment Permit; Spat and seed importation permit; and export permits for those who wish to export. In Saldanha Bay farmers lease water space from the National Ports Authority (Portnet), the directors and state representatives interviewed described the fees from Portnet excessive, the most expensive in the world. The National Aquaculture Policy Framework for South Africa 2013, intends to correct several problems inside the country's aquaculture sector, namely to simplify the permitting process, and to pass food quality and safety legislation for compliance with international standards.

1.10 Physical description of Saldanha Bay

Saldanha Bay is located on the South African west coast, about 100km north of Cape Town, and is directly connected to the shallow tidal Langebaan Lagoon. The Bay and the lagoon are considered areas of great biodiversity in the country. A number of marine areas around the Bay have been declared protected, and Langebaan Lagoon and much of the surrounding land are part of the West Coast National Park (Clark et al., 2012).

Saldanha Bay consists of an outer Bay and an inner, shallower Bay (Figure 5). This was considerably altered in in the 1970's with the construction of a causeway for iron ore and oil terminals (Figure 6). This created two sectors: the Big and Small Bay (Pitcher et al., 2015; Clark et al., 2012)). The area of the lagoon is about 40 km^2 (Flemming, 1977) the Bay's area is about 45 km^2 (Grant et al., 1998).

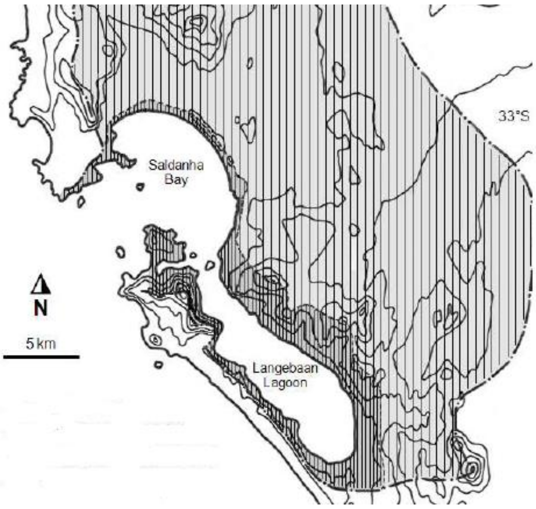


Figure 5 – Saldanha Bay illustration before iron ore construction. Source: B. W. Flemming, (1977)

Figure 6 – Saldanha Bay actual satellite picture. Source: Google maps.

South Africa is exposed to strong climatic influences: The South Atlantic Ocean high pressure system that lies to southwest; The Indian Ocean high pressure system in the east; and the westerlies wind system to south where low pressure systems develop; This results in strong wind systems along the country (Kruger et al., 2010). The prevailing winds tend to be equatorward, parallel to the coast, inducing upwelling (Harris, 1978). During the winter the northwesterly winds dominate.

Upwelling is a phenomenon that occurs when a surficial water layer drives away from the coast, and the bottom cold and nutrient rich water comes to the surface, replacing the upper layer near the coast. The cause of upwelling can be wind stress, parallel to coast that results in a current opposite to the coast (Coriolis Effect), or when the water near the coast is warmer than the ocean water resulting in a similar current effect (Monteiro and Largier, 1999).

The upwelling season in Benguela lasts around 10 months, from August to May at which time the Bay is typically stratified. The local winds can affect the Bay waters in two ways. It drives upwelled bottom water into the Bay, enhancing thermal stratification. On the other hand, these winds can drive the vertical mixing and entrainment of intruded upwelled waters. Typically coastal winds drive upwelling and local winds mixing. In Saldanha Bay, upwelling process is very important for water renewal, and during such events the residence time is half the normal time (Monteiro and Largier, 1999). Nutrient input into the Bay is largely dependent on the advection of cold NO_3^- rich bottom water into the Bay and the vertical turbulent flux across the thermocline.

Monteiro and Largier, (1999) propose a 4 phase explanation of the upwelling process in the short term. First the equatorward wind drives vertical mix and upwelling, there is an intrusion of the cold bottom water, in phase three there is formation of a thermocline, and in the last phase the bottom cold water drains away. During phase 2 there is nutrient availability and the only limitation for phytoplankton production is light. During phase 3, thermocline formation limits NO_3^- supply to the surface layer and nutrient availability becomes the main limitation to production.

1.11 Use conflicts

Water quality is very important in aquaculture, as it influences the farmed species health. Good water quality results in an increased production efficiency and product quality (Boyd and Tucker, 2012) beyond that shellfish producers must meet public quality standards for water quality and are subject to quality control in several countries including South Africa. Therefore farmers cannot tolerate any activity that changes their farms' water quality (Shumway et al., n.d.). Filter-feeding aquaculture uses an important resource, space, by which it can conflict with other activities, such as, wild stock fisheries, mineral extraction, and tourism, as it may occupy areas where these activities will not be allowed to occur (Gibbs, 2004). Therefore shellfish aquaculture can conflict with all activities that may compete for space use or affect water quality.

There are a number of activities in Saldanha Bay that can affect water quality, such as:

- Port
- Liquid petroleum facility
- Shipyard
- Reverse osmosis desalinization plants
- Sewage discharges
- Fish processing plant
- Urban development
- Tourism

The port expansion, requires extensive dredging and marine blasting, and the fish processing factories discharge effluents with significant quantities of organic material, which can lead to deterioration in water quality in the Bay. Ships using the Port of Saldanha discharge large volumes of ballast water, which represents a great risk, of introducing alien species and contaminants into the Bays water. Urban development increases the volume of storm water entering the Bay, which is a major source of non-point pollution and typically contains contaminants such as, bacteria, nutrients, hydrocarbons, pesticides, solvents, metals, and plastics. The population growth results in increased pressure through increased waste waters (Clark et al., 2012).

1.12 Carrying capacity studies

Many studies calculate carrying capacity for finfish and shellfish production using different scales, sites, and methods. Most of these are studies that use spatially resolved ecological models, which divide the ecosystem in boxes and simulate hydrodynamic transport (Duarte et al., 2003). Bivalves are dependent on the ecosystem's primary production, and therefore, mathematical models can be very useful in understanding and simulate the interactions in such ecosystems. The most commonly used models are the bio-physical ones that consider the influence of hydrodynamics on transport and mixing, biochemistry, and population dynamics (Dowd, 2005; Franco et al., 2006). These models offer considerable potential for simulating the growth of species, and determining of the conditions providing best growth potential, both very useful to aquaculture management.

Several studies built ecological models, trying to determine the carrying capacity for a certain species production in different study sites all around the world: Ferreira et al., (2008) for mussel and oyster production in four loughs in Northern Ireland; Filgueira et al., (2014) for oyster production in the Richibucto Estuary, eastern Canada; Brigolin et al., (2009) mussel farming in northern Adriatic Sea in Italy; Luo et al., (2001) for menhaden production in Chesapeake Bay; Duarte et al., (2003) Sungo Bay, Shandong Province, People's Republic of China for IMTA of bivalve shellfish and kelp; Bacher et al., (1997) for mussel in Marennes-Oléron Bay, France; Guyondet et al., (2010) mussel production in Grande-Entrée Lagoon (GEL) ecosystem, Canada.

1.13 Bivalve studies in Saldanha Bay

There are a number of studies relevant for shellfish production carrying capacity in Saldanha Bay. Pitcher et al., (2015) investigated the Bay's productivity using the light-and-dark bottle oxygen method, and compared methods on primary production determination. Henry et al., (1977) studied the seasonal variability of primary production in Saldanha Bay and Langebaan Lagoon Monteiro and Brundrit, (1990) analysed the effects of the variable characteristics of coastal waters on chlorophyll annual and monthly variance. Pitcher and Calder, (1998) estimated phytoplankton biomass in the Bay, analysing the physical and chemical environment that conditions it. These studies focus mainly on phytoplankton production, which is important because phytoplankton stands as the available food for shellfish production. Grant et al. (1998) studied Saldanha's Bay carrying capacity, using the Bay's carbon budget. It compared an estimate of phytoplankton carbon production in the Bay with an estimate of the phytoplankton carbon consumption by the existing mussel production.

Other studies regarding shellfish production were made for Saldanha Bay impact of mussel culture on the substrate by Stenton-Dozey et al., (2001); Stenton-dozey et al., (1999), (see above). Probyn et al. (2000) studied the physical factors causing the seasonal appearance of toxic algal blooms in the Bay. Probyn et al., (2001) summarize the effects of these algal blooms on shellfish production. Anderson et al., (1999) studied the potential of fish effluents for the production of *Gracilaria gracilis,* for increasing both production efficiency and nutrient removal from the water.

Olivier et al., (2013) investigated the possible social benefits of cultivating oysters and mussels in Saldanha Bay at carrying capacity. Mussel production totals of one project are combined with projected potential estimates determined in other studies to determine carrying capacity.

2 Methods

This work focused on the construction of an ecological model. This model aims to simulate the ecological dynamics of Saldanha Bay, creating a powerful management tool for system analysis. The model may be used to predict how the different ecological variables would respond or change to the introduction of new inputs, and to simulate different shellfish production scenarios and determine the Bay's carrying capacity for this industry. This was carried out using data which was collected for other studies adapting it into an ecological model and a shellfish individual growth model.

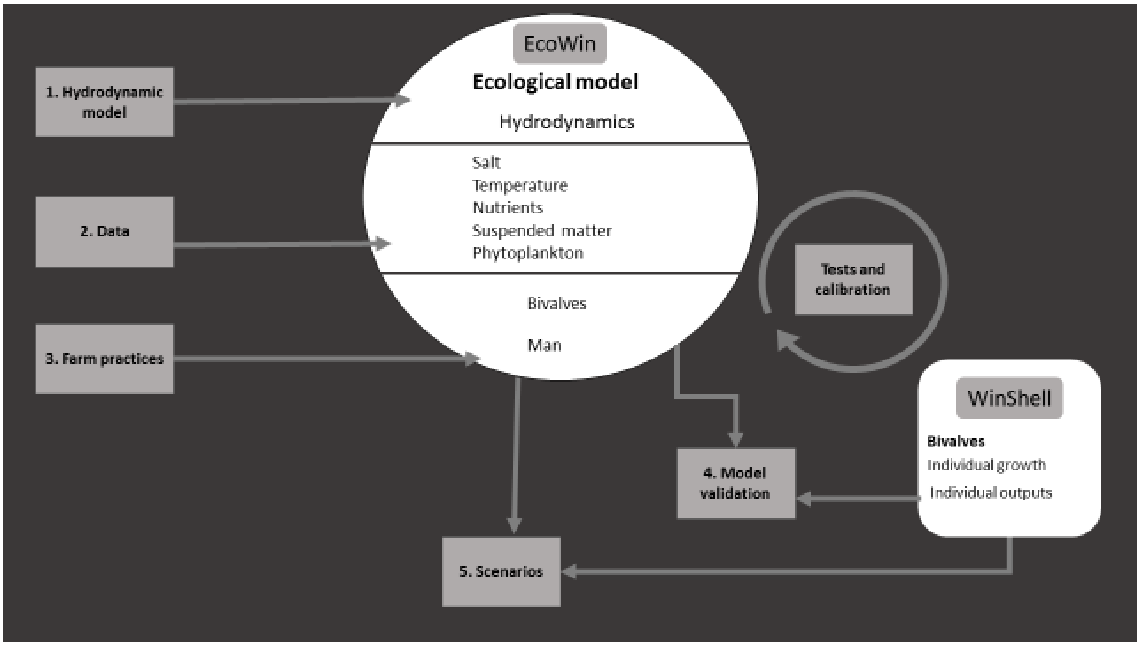


Figure 7 – Simplified modelling framework used.

This model was built using EcoWin, an object oriented program developed for building ecological models. The program is described in more detail in *Tools* section. The model uses 8 objects: hydrodynamics; light, water temperature, nutrients, phytoplankton, suspended particle matter, bivalve shellfish, and Man. Hydrodynamics includes the salinity state variable and is responsible for particles and dissolved substances transport inside the Bay. These components use different data sources. They are inserted in two ways: forced in each box, for which are named forcing functions; forced in boundaries, named state variables; or derived from other variables.

The water temperature and light are forced in each box. Which means that these variables have the same curve every year which is not influenced by any of the other variables. These curves use time as the independent variable.

Salinity, nutrients, particles, and phytoplankton are forced in the boundaries, in this case only the ocean boundaries. This means the ocean boundaries have forcing functions for each of these variables (in this case, also for each of the two ocean layers). Each box has a given initial value for each state variable, that will afterwards change dynamically, influenced by the water coming from the boundaries and the other variables.

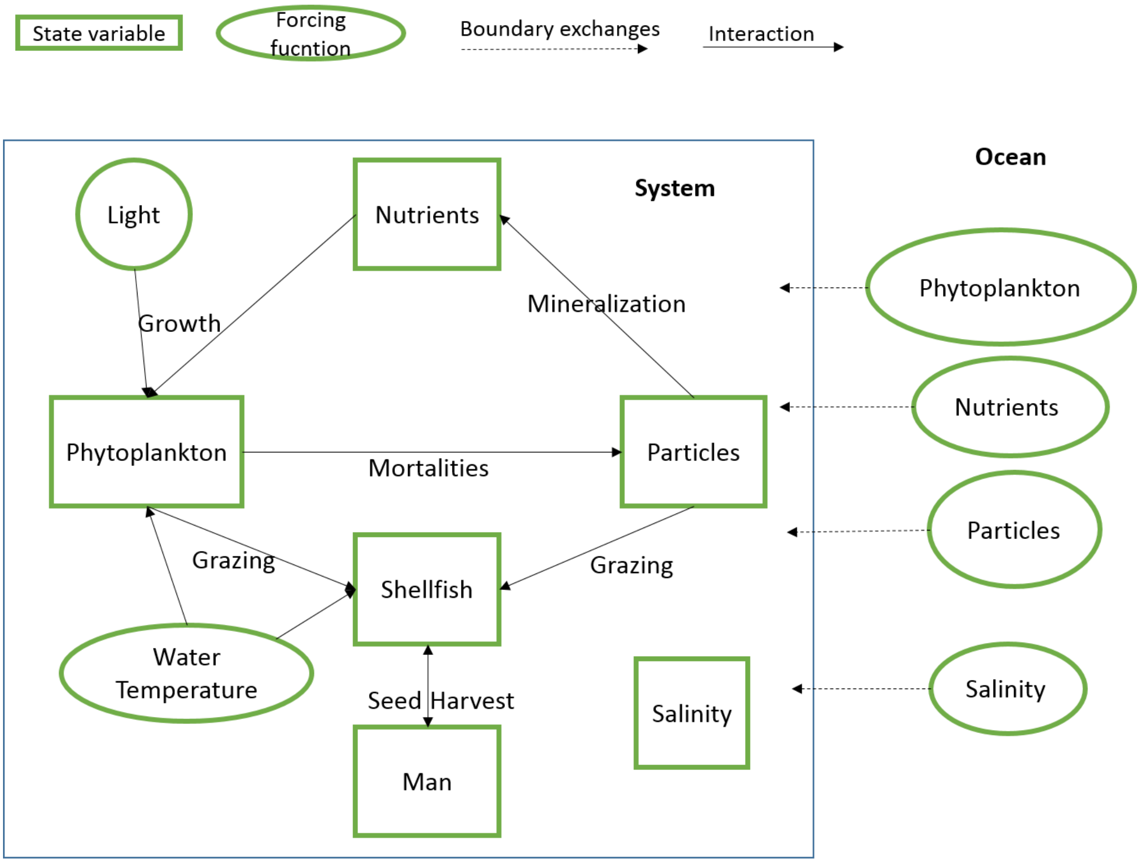


Figure 8 – Conceptual model schematization.

Figure 8 shows how physical layout of the model is. The Bay is divided in 8 boxes, the 4 main areas of the Bay divided vertically in two (one upper and one lower box). There is one area for the Big Bay, one for the Small Bay, another for the Outer Bay, and one for Langebaan Lagoon, only the Outer Bay communicates directly with the ocean. The hydrodynamic model, described further, is based on this box system.

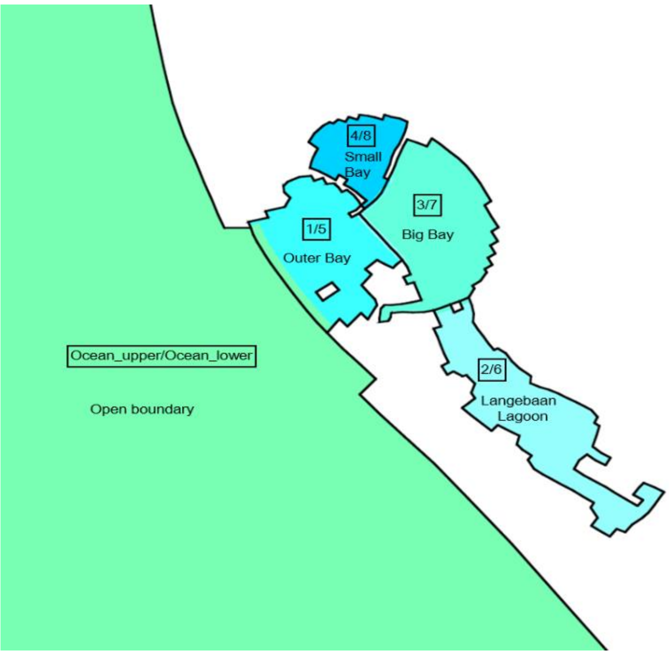


Figure 9 – Models box scheme organization.

2.1 Tools used

In order to combine the variables and build scenarios EcoWin was used in order to resolve hydrodynamics, biochemistry, and population dynamics for target species. EcoWin works with a series of self-contained objects that correspond to sub-models in other approaches. The model can be divided in two main parts, the shell module and the ecological objects. The shell module communicates with the various ‘ecological’ objects, provides the user interface, and executes other maintenance tasks (Ferreira, 1995).

Each object contains its own properties (state variables, parameters, etc.) and methods (functions). Those methods control interactions between state variables and can be easily changed, through inheritance (Ferreira, 1995). Objects have some important properties that make them interesting for ecological modelling: encapsulation, inheritance, polymorphism, modularity, reliability, and reusability. These assets provide flexibility to EcoWin, simplify further development of descendant objects, reduce the propagation of errors, and promote code re-use (Ferreira, 1995).

EcoWin works as a platform for integration of various models, adding functionalities of its own. It is typically used for multi-year simulations, dealing e.g. with multiple aquaculture cycles and species. The hydrodynamic data were obtained from the application of the delft 3D model (Deltares, applied by Luger & Monteiro, CSIR – pers. Com).

The phytoplankton biomass turns into particulate organic matter (POM), through mortalities, which in turn mineralized into inorganic nutrients such as nitrate and phosphate. Nutrients are consumed by phytoplankton which in turn is consumed by “Shellfish” object. “Shellfish” is harvested and seeded by “Man” object. Light, water temperature, and salinity influence the phytoplankton growth, water temperature, and salinity will influence the shellfish growth. Figure 7 aims to schematize and resume the model’s concept visually.

This study also used a program named Winshell to help with the shellfish object calibration. The model simulates the individual growth of oysters, clams, and mussels. This program is designed to determine how this bivalve will grow in a certain location. The user may insert its local water specifications, such as food availability, water temperature, salinity, and suspended matter. It is also possible to choose the seed size and seeding period. This model shows tabulated results of the shellfish growth, energy dynamics, and total uptakes from the environment.

2.2 Data

With the help of Dr Grant Pitcher, from the University of South Africa, data from two different studies was acquired. Smith and Pitcher, (2015) collected data for temperature, salinity, dissolved oxygen, chlorophyll, nutrients, and light at various water depths, over a period of one year, with a bimonthly frequency, for 8 stations distributed across the Bay. This data covers the water column vertically and stations are distributed across two main areas, the Big Bay and the Outer Bay, as Figure 9 illustrates. These two zones are equivalent to boxes 1 and 5 (Outer Bay) and boxes 3 and 7 (Big Bay). Stations 1, 2, 3 and 4 are inside the Big Bay area and the remaining in the Outer Bay.

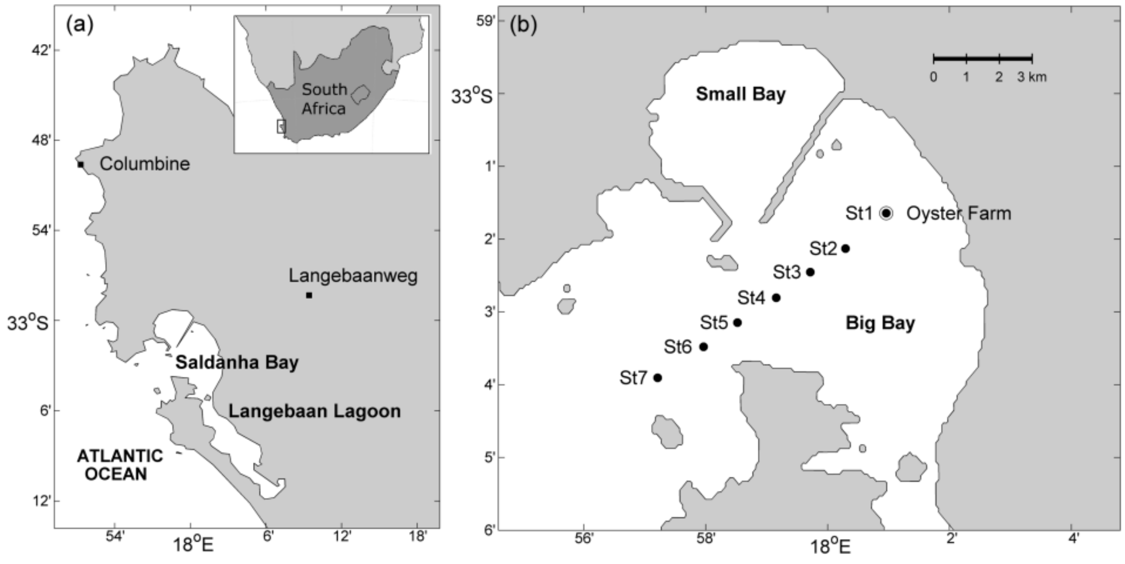


Figure 10 – Sampling stations spatial distribution inside the Bay. Source: (Smith and Pitcher, 2015)

Sampling for suspended particle matter and particle organic matter was made by Probyn and is explored in Monteiro and Largier, (1999), and used in this study. This study determined the particle composition in several positions across the Bay in 1997, between the 25 of February and 8 of March as shown in Monteiro & Largier (1999). The Figure below illustrates the sampling areas stations.

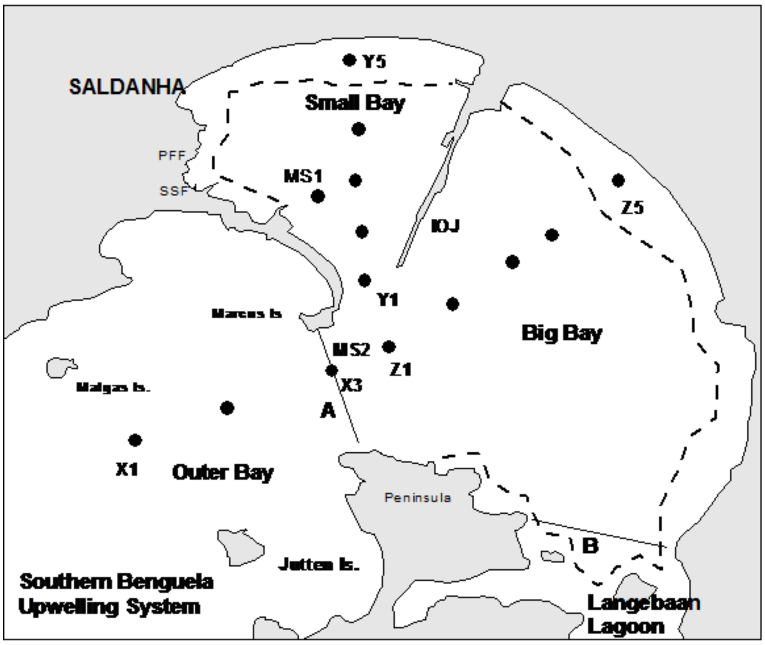


Figure 11 – Sampling stations for particle matter spatial distribution. Source:(Monteiro and Largier, 1999)

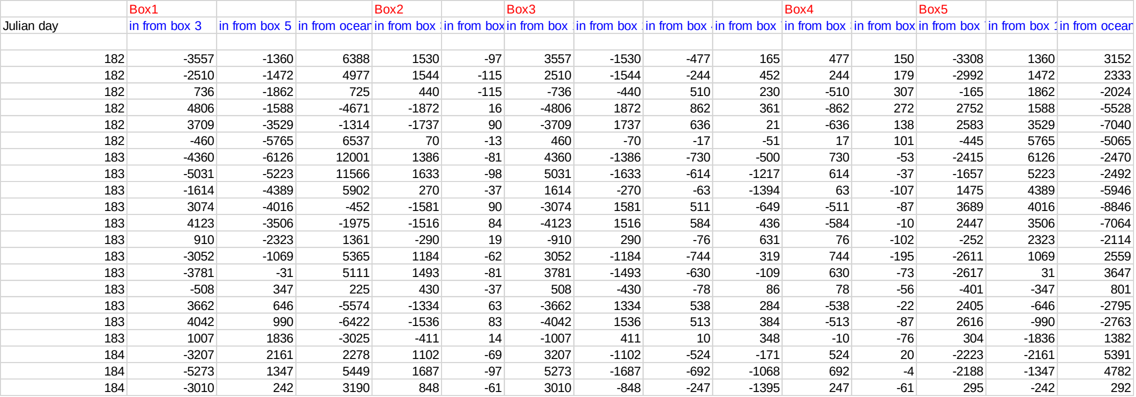
2.3 The Hydrodynamic model

The *hydrodynamics* object contains 4 variables: salinity; tracer; volume; and evaporation; Salinity is forced in the ocean border and evaporation is forced with a constant value all year. Volume is forced with an initial value, and the rest evolves dynamically with the fluxes and evaporation effects, the tracer is used to test the Bay residence time.

The hydrodynamic model was developed specifically for the study site by Stephen Luger, yet the model has never been tested. Thus the first step of this study aims to analyse if this model works properly.

The model works with water fluxes (m^3s^{-1}) between adjacent boxes. The flux values are given every 2 hours for one complete year counting from the 182th day and ending in the 547th.

This means that there are 12 fluxes per day given to each trade. The model is organized in 8 areas, each belonging to one of the 8 boxes. Each area has as many columns as the number of boxes that border it. Each column has the fluxes coming in from one of these boxes. If Box Y has a column *in from box X*, Box X has one *in from Box Y*, these columns are symmetric. Figure 15 is a part of the table, used to illustrate how the model works.



	Box1			Box2		Box3				Box4		Box5		
Julian day	in from box 3	in from box 5	in from ocean	in from box	in from box	in from box	in from box	in from box	in from box	in from box	in from box	in from box	in from box	in from ocean
182	-3557	-1360	6388	1530	-97	3557	-1530	-477	165	477	150	-3308	1360	3152
182	-2510	-1472	4977	1544	-115	2510	-1544	-244	452	244	179	-2992	1472	2333
182	736	-1862	725	440	-115	-736	-440	510	230	-510	307	-165	1862	-2024
182	4806	-1588	-4671	-1872	16	-4806	1872	862	361	-862	272	2752	1588	-5528
182	3709	-3529	-1314	-1737	90	-3709	1737	636	21	-636	138	2583	3529	-7040
182	-460	-5765	6537	70	-13	460	-70	-17	-51	17	101	-445	5765	-5065
183	-4360	-6126	12001	1386	-81	4360	-1386	-730	-500	730	-53	-2415	6126	-2470
183	-5031	-5223	11566	1633	-98	5031	-1633	-614	-1217	614	-37	-1657	5223	-2492
183	-1614	-4389	5902	270	-37	1614	-270	-63	-1394	63	-107	1475	4389	-5946
183	3074	-4016	-452	-1581	90	-3074	1581	511	-649	-511	-87	3689	4016	-8846
183	4123	-3506	-1975	-1516	84	-4123	1516	584	436	-584	-10	2447	3506	-7064
183	910	-2323	1361	-290	19	-910	290	-76	631	76	-102	-252	2323	-2114
183	-3052	-1069	5365	1184	-62	3052	-1184	-744	319	744	-195	-2611	1069	2559
183	-3781	-31	5111	1493	-81	3781	-1493	-630	-109	630	-73	-2617	31	3647
183	-508	347	225	430	-37	508	-430	-78	86	78	-56	-401	-347	801
183	3662	646	-5574	-1334	63	-3662	1334	538	284	-538	-22	2405	-646	-2795
183	4042	990	-6422	-1536	83	-4042	1536	513	384	-513	-87	2616	-990	-2763
183	1007	1836	-3025	-411	14	-1007	411	10	348	-10	-76	304	-1836	1382
184	-3207	2161	2278	1102	-69	3207	-1102	-524	-171	524	20	-2223	-2161	5391
184	-5273	1347	5449	1687	-97	5273	-1687	-692	-1068	692	-4	-2188	-1347	4782
184	-3010	242	3190	848	-61	3010	-848	-247	-1395	247	-61	295	-242	292

Figure 12 – Hydrodynamic model illustration.

The key features analysed are the tidal change and the boxes volume evolution, the number of tides per day and the tidal amplitude. The volume evolution in each box was analysed in order to understand if the tidal movement is synchronized, and if they maintain the mean volume during the year. Tides were counted and analysed in amplitude to check if are accordingly to the real values in Saldanha Bay.

An adaptation of this same model was then used in EcoWin. This model is a part of the initial model cut in 91 days (3 months). By using this model, in a study that aims to model the Bay for several years, there are some yearly tidal variations that are lost, namely the equinoctial tides. This implies some simplification of the hydrodynamic model and therefore some loss of precision.

Two outputs were taken in EcoWin, namely salinity and volume tables for each box for 10 years. Salinity was tested with different conditions, initial in each box and coming from the ocean along the year.

2.4 Forcing Functions

Light and water temperature were the two only forcing functions used. This means that their value in each box will be defined strictly by a predefined curve and will not be changing dynamically with the other objects. This is made this way because the effects of other variables are insignificant and because it is too complex and unnecessary to model. This kind of approach has been successfully utilized in other studies such as Bacher et al., (1997); Ferreira et al., (2008, 2007).

2.5 Temperature

Water temperature is a critical component of the ecological model, since it is rate-limiting for key processes such as phytoplankton production and bivalve clearance rates. In this application of EcoWin, temperature was simulated as a forcing function by fitting a family of curves to measured data. Since temperature distributions were not spatially homogenous, which is unsurprising given the model framework of upper and lower boxes, and also the differences in circulation between the various Bays and the lagoon, data from different sampling stations (Fig JGF1) were used to derive polynomial functions for each box. A specific descendant object was then coded in EcoWin to simulate the water temperature in various parts of the Bay over an annual cycle. For multi-annual simulations, this cycle is iterated.

The available data from Smith and Pitcher, (2015) covers only for boxes 1, 5, 3 and 7. According to Pitcher and Calder, (1998) the water temperature in Small Bay is slightly higher, but similar, to Big Bay. Due to the lack of data for the Small Bay and this similarity in the temperature numbers with the Big Bay, the same curves were assumed for both areas. The lack of data for Langebaan lagoon made it also necessary to improvise: Station 1 is the one with the most similar characteristics to Langebaan, low depth and higher temperatures (Henry et al., 1977), therefore this station temperatures were assumed to describe the profile inside the lagoon, and used to determine the curve for Boxes 2 and 6.

Station 7 is the available closest data from the ocean boundaries. For this reason all the curves for salt nutrients and phytoplankton coming from the ocean were drawn from the data in this station, and excluded from the calculus for the Outer Bay. Table to resumes which stations were used for each box.

Table 2 – Stations used for each box group.

Boxes	**Stations**
1/5	6; 5
3/7 and 4/8	4; 3; 2;
2/6	1

By the lack of data for November, these values were extrapolated for the upper and lower box for each station, by comparison with station 1. The values for the lower box were considered to be the same as in January and in the upper box the value was determined considering a linear variation between September and January (next year).

The depth used for boxes 1 and 3 was 14,96m and 6,64m respectively, box 2 is much shallower with a depth of 1,91m. The lower boxes used data counting from the respective upper box depth till the bottom. The values for November, in all stations except 1, had to be extrapolated. The similarities between curves allowed the use of station 1 results (box 2 and 6) to guide the extrapolation for the remaining ones.

The curves were determined, using 6 points for the 6 available months, and a trend line was adapted, typically a polynomial one with the necessary correlation. Which by the table of Sokal and Rohlf (James and Sokal, 1995) is the R≥ 0.811 to 95% confidence.

The polynomial functions were then determined, and the values extrapolated with the adjusted functions (starting in the 18th and end in the 309th day) for the remaining days would not make sense for some of the boxes. Therefore composite functions were developed for some, using a linear function for the first 18 days, or between 309th and the 365th every time the value for these periods was too different. The following functions in Figure 13, show the equations use for each box, temperature (ºC) being the dependent variable and for time the independent one.

Box 1

$$\boldsymbol{y} = \begin{cases} -0{,}00000001229\boldsymbol{x}^4 + 0{,}00000792921\boldsymbol{x}^3 - 0{,}00157334324\boldsymbol{x}^2 + 0{,}09711211252x + 12{,}75252362904, & 1 \le x \le 309 \\ -0{,}02810x + 23{,}10357, \quad 309 < x \le 365 \end{cases}$$

Box 2

$$\boldsymbol{y} = \begin{cases} 0{,}000001568x3 - 0{,}000502405x2 + 0{,}001490460x + 20{,}230979965, & 1 \le x \le 309 \\ 0{,}02687x + 10{,}42470, \quad 309 < x \le 365 \end{cases}$$

Boxes 3 and 4

$$\boldsymbol{y} = 0{,}0001672\boldsymbol{x}^2 - 0{,}0625482\boldsymbol{x} + 19{,}2913877, \qquad 1 \le \boldsymbol{x} \le 365$$

Box 5

$$\boldsymbol{y} = \begin{cases} -0{,}000001538\boldsymbol{x}^3 + 0{,}000689182\boldsymbol{x}^2 - 0{,}069657333x + 11{,}893721175, & 1 \le x \le 309 \\ 0{,}02340x + 3{,}28452, \quad 309 < x \le 365 \end{cases}$$

Box 6

$$\boldsymbol{y} = \begin{cases} 0{,}0000011501x3 - 0{,}0003824031x2 + 0{,}0016154650x + 18{,}9692831999, & 1 \le x \le 309 \\ 0{,}04400x + 2{,}90871, \quad 309 < x \le 365 \end{cases}$$

Boxes 7 and 8

$$\boldsymbol{y} = \begin{cases} -0{,}000001101\boldsymbol{x}^3 + 0{,}000494752\boldsymbol{x}^2 - 0{,}050191880x + 12{,}376925798, & 1 \le x \le 309 \\ 0{,}01792x + 5{,}78498, \quad 309 < x \le 365 \end{cases}$$

Figure 13 – Temperature forcing functions used for each box.

2.6 Salinity

Salinity was forced from the ocean boundary. Station 7 is the one closer to the ocean so it was considered to have the most similar conditions to the ocean. The average salinity evolution during the year was made with similar methods to the temperature, using the box 1 lower limit as the limit between ocean upper layer and ocean lower layer. As the available data is only till September it was not extrapolated, the program does the rest alone. Figure 14 illustrates Salinity evolution in ocean boundary

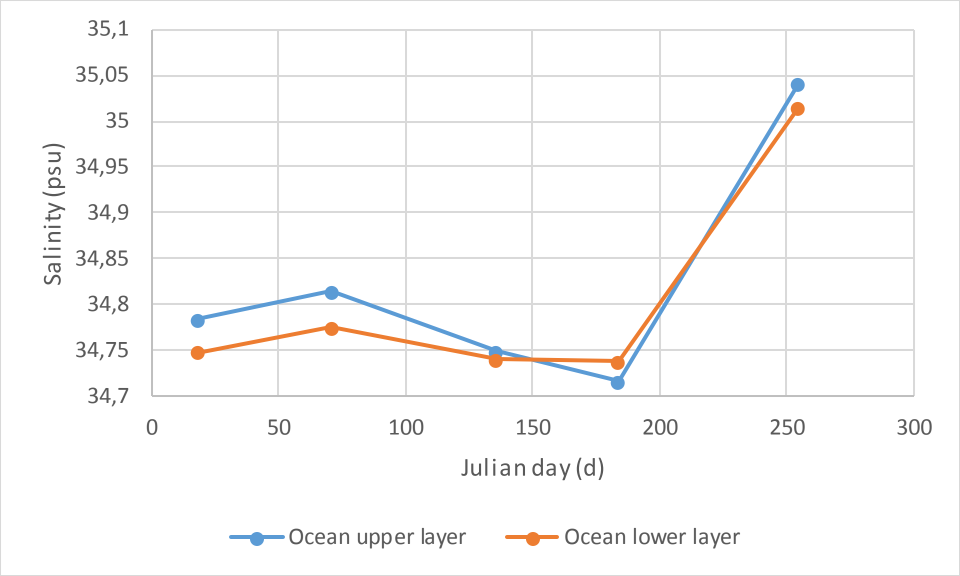


Figure 14 – Ocean boundaries salinity curves.

Salinity at the ocean border shows lower values in the winter and peak in spring. The maximum value is about 35 psu and the lower values about 34.7 psu, both in the ocean upper layer. The average salinity in the ocean is 34.8 psu.

Initial salinity values were defined for all boxes, with the absent of a determined value for day 1 (the 1th of January) the value for the 18th was used. This value was determined using the same methods as for temperature. Table 3 shows the determined values for each box.

Table 3 – Initial salinity conditions for each box.

Box	**Box 1**	**Box 2**	**Box 3/4**	**Box 5**	**Box 6**	**Box 7/8**
Salinity (psu)	34.79	34.86	34.80	34.74	34.78	34.76

2.7 State variables

Pelagic state variables are forced at the ocean boundary. This means that there is an independent annual flux for each variable coming from the ocean, and the rest is dependent on mixture, transport, consume or new inputs.

The *nutrients* object contains 5 state variables: ammonia; nitrite; nitrate; phosphate; and silica; All of these state variables are forced in the ocean layer.

The *phytoplankton* object uses: the phytoplankton biomass; and others not analysed. The phytoplankton biomass growth is dependent on light, nutrients, exudation, respiration (light and dark), natural mortality, and removal by other organisms such as filter-feeding shellfish.

Suspension matter object has 2 state variables: suspension matter; and particulate organic matter; both are forced in the ocean layer, and are affected (inside each box) by phytoplankton mortality, deposition processes, and mineralization.

2.8 Nutrients

This object was processed similarly to the remaining to the following variables: ammonia, nitrite, nitrate, phosphate, and silica. The only difference was that the only data available for these nutrients was for station 1 (the one further from the ocean boundary). Figure 15 describe the boundary conditions for each nutrient.

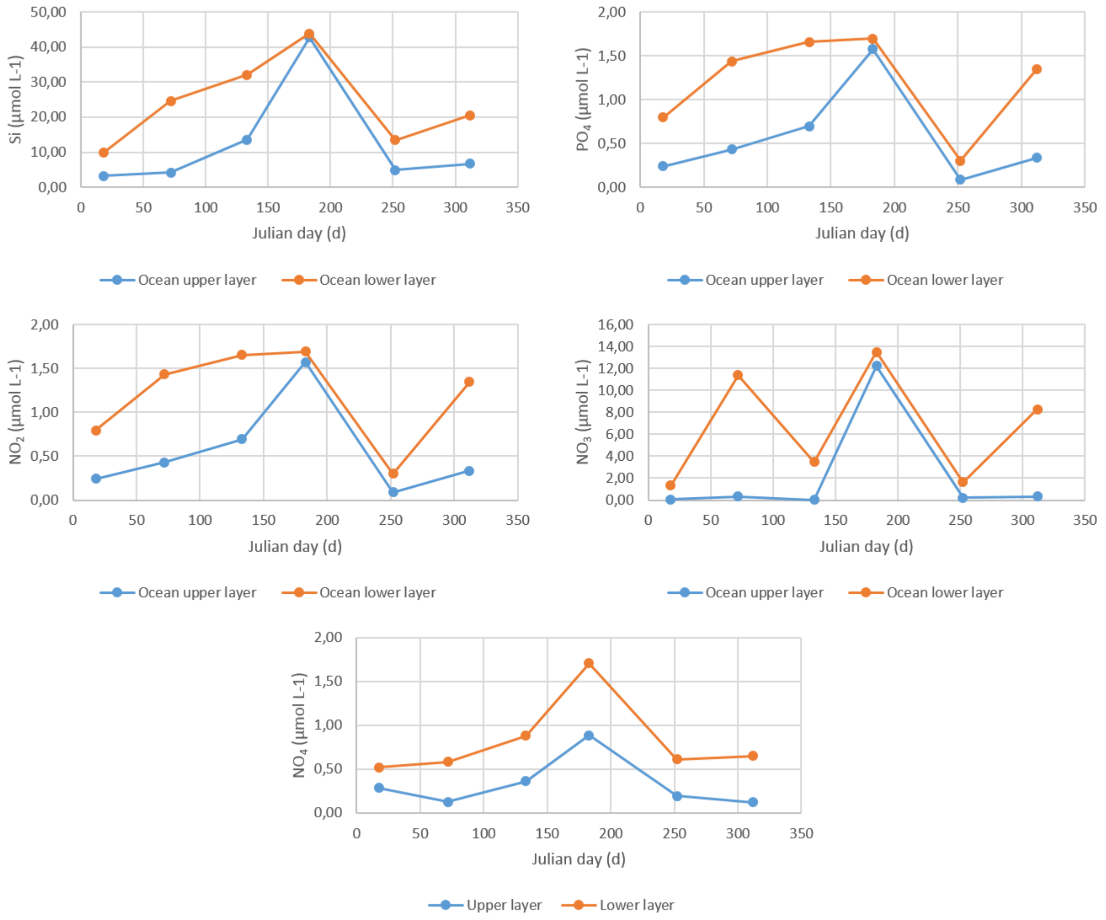


Figure 15 – Boundary conditions for silica, phosphate, nitrite, nitrate and ammonia.

By the initial values for each box lack of data, each upper box got the same value as the initial one for ocean upper layer and the ones in the layer idem. Table 4 shows the attributed values to each box.

Table 4 – Initial conditions for each box

	Box 1	**Box 2**	**Box 3**	**Box 4**	**Box 5**	**Box 6**	**Box 7**	**Box 8**
NH_2 (µmol L^{-1})	0.01	0.01	0.01	0.01	0.10	0.10	0.10	0.10
NH_3 (µmol L^{-1})	0.07	0.07	0.07	0.07	1.35	1.35	1.35	1.35
NH_4 (µmol L^{-1})	0.28	0.28	0.28	0.28	0.52	0.52	0.52	0.52
Si (µmol L^{-1})	3.27	3.27	3.27	3.27	9.80	9.80	9.80	9.80
PO_4 (µmol L^{-1})	0.24	0.24	0.24	0.24	0.80	0.80	0.80	0.80

2.9 Suspended Matter

A series of data collected by Probyn (unpublished) - station positions described in Monteiro and Largier, (1999) was used to determine suspended particulate matter (SPM) and particulate organic matter (POM). These data set came with SPM and particulate organic carbon (POC). To determine particulate organic matter the following formula was used:

$$POM = r * POC$$

Being r = 1,88 (Lam and Bishop, 2007). These data was only available for some days of February and March, but for a series of areas in the Bay, as Figure 16 shows. For the ocean boundary transect A was used. For the Big Bay initial values the Z values, for the Small Bay the Y values and for Langebaan Z5. The initial values for each box are as shown in table 5.

Table 5 – Initial conditions for each box to POM and SPM

	Box 1	**Box 2**	**Box 3**	**Box 4**	**Box 5**	**Box 6**	**Box 7**	**Box 8**
POM (mg L^{-1})	4	4	4	4	4	4	4	4
SPM (mg L^{-1})	37	56	44	34	10	16	23	35

The ocean boundary curves are described in the charts below. The model extrapolated the curve for the rest of the year alone. Both SPM and POM have considerably higher concentrations in the upper layer.

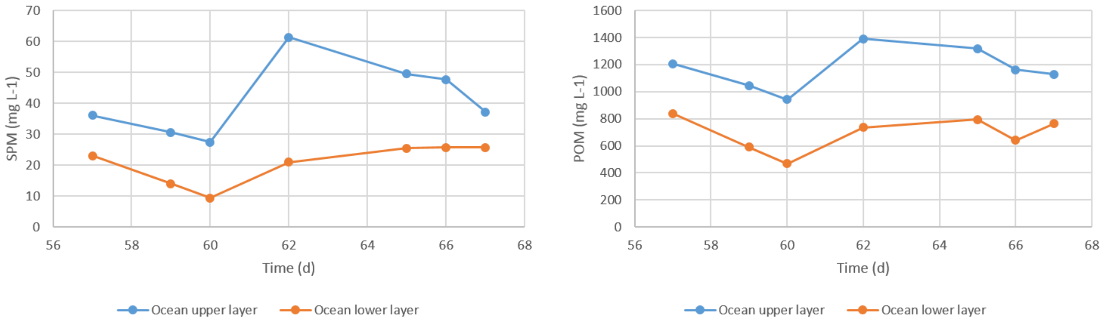


Figure 16 – SPM (left side) and POM (right side) boundary conditions.

2.10 Phytoplankton

Phytoplankton boundary conditions curve (Figure 17) was drawn using the same methods as for *Nutrients*. The curve shows a peak around September.

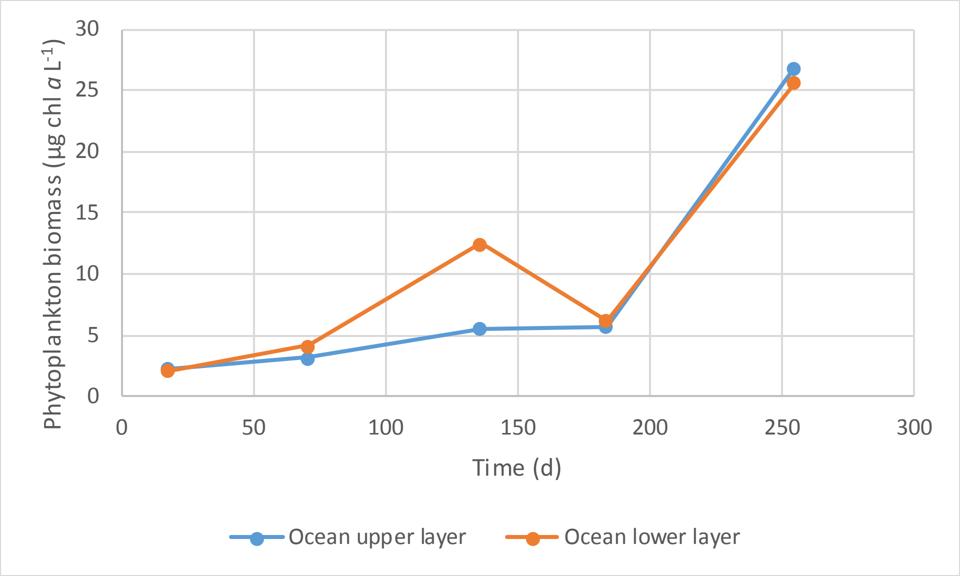


Figure 17 – Boundary phytoplankton biomass.

Using the available data the initial values for each box were calculated and inserted into the model. Table 6 shows the initial values calculated for each box.

Table 6 – Initial phytoplankton biomass for each box

Box number	**Box 1**	**Box 2**	**Box 3**	**Box 4**	**Box 5**	**Box 6**	**Box 7**	**Box 8**
Phytoplankton biomass (µg chl *a* L^{-1})	8.6	2.3	5.5	5.5	3.9	2.1	11.0	11.0

2.11 Parameters

Standard parameterization from other models such as Belfast Lough model built by Ferreira et al., (2008), were used and adjusted in this model system where applicable. The parameters used to regulate phytoplankton are shown in the Table 7. “Pmax” and “Ks” are used in Michaelis Menten equation and regulate the Phytoplankton growth based on nutrient concentration. The following equation represents the Michaelis-Menten equation for phytoplankton growth; P is phytoplankton growth and [N] nutrient concentration.

$$P = \frac{Pmax * [N]}{Ks + [N]}$$

“Iopt” is used in Steele, (1962) equation and is defined as the optimum light for phytoplankton production, above this value there is photo-inhibition, and the production decreases. This equation is described below, being “Ppot” the potential production and “I” the light energy:

$$Ppot = \frac{Pmax * I}{Iopt} * Exp(1 - \frac{I}{Iopt})$$

“Maintenance respiration” and “Respiration coefficient” are the energy consumed during the night and during production process respectively, used in the total budget equation.

Table 7 – Phytoplankton parameters used.

Parameter	**Value**	**Description**
Pmax (h^{-1})	0.3	Maximum phytoplankton production
Ks (µmol L^{-1})	2	Half saturation constant
Lopt (W m^{-2})	200	Optimum light intensity
Dead loss (d^{-1})	0.01	Percentage of dead loss per day
Maintenance respiration (d^{-1})	0.4	Energy spent during low production (night)
Respiration coefficient (d^{-1})	0.3	Energy spending rate during production (day)

The parameters used for suspended matter are shown in Table 8. “SPM resuspension” and “Turbulence” influence the SPM vertical movement inside each box. “POC fraction” defines the percentage of SPM that is POC, “POM mineralization rate” is the ratio that defines how much POM mineralizes per day. “POM to nitrogen” and “POM to phosphorus” define the POM mineralization to N and P.

Table 8 – Suspended particle matter used parameters.

Parameter	**Value**	**Description**
SPM resuspension (d^{-1})	0.50	Resuspension ratio to SPM
Turbulence (d^{-1})	0.10	Turbulence ratio
POC fraction (no units)	0.16	SPM fraction of POC
POM mineralization rate (d^{-1})	0.060	POM mineralization rate
POM to nitrogen (DW to N)	0.046	POM to nitrogen in mineralization
POM to phosphorus (DW to P)	0.0034	POM to phosphorus in mineralization

2.12 Shellfish

Winshell was used to test the growth potential of the two bivalve species in both boxes, using temperature, SPM, POM, salinity, and phytoplankton results from the model. These values were only used for calibration, and do not consider competition, as the growth is considered individually.

In order to simulate the reality in Saldanha at the moment, several farmers were contacted for information about their culture practices, location, areas under production, and production values. Small Bay shelters the production of both mussel and oyster, as Big Bay only for oysters. The farms are located only in the upper boxes, namely boxes 3 and 4.

There are 5 companies producing shellfish in Saldanha Bay, 3 produce oysters and 2 mussels. A total of 45 hectares is leased for oyster production (30 in Big Bay and 15 in Small Bay) and the annual production is about 700 tonnes. Most of the oyster production lies in Big Bay (about 70%) and the major producer is Saldanha Bay Oyster Company, which is responsible for about 75% of it. Mussel production uses about 80 hectares, all in Small Bay, and produces about 2400 tonnes per annum, Blue Ocean Mussels is estimated to produce about 1400 tonnes and Imbaza Mussels 1000 tonnes. Table 9 summarizes this information.

Table 9 – Companies working in Saldanha Bay, respective annual production and licensed area.

Company	**Product**	**Location**	**Area (ha)**	**Annual production (ton)**
Oyster	Saldanha Bay Oyster Company	Small Bay and Big Bay	35 (10 SB + 25 BB)	525
	West Coast	Big Bay	5	140
	Blue Safire Pearls	Small Bay	5	40
Total	-	-	45	705
Mussel	Imbaza Mussels	Small Bay	30	1000
	Blue Ocean Mussels	Small Bay	50	1000
Total	-	-	80	2000

Oysters are seeded with approximately 4 g, in both Bays, and mussel production uses mostly natural seeding, which for modelling purposes was assumed to be around 0.65 g. Mussel weight at harvest is between 25 and 40 g, and oysters around 70 g. Therefore the model is programed to harvest mussels from 25 g and oysters from 61 g. The defined number of seeds for mussels was 50 million, for oysters around 2 million in Small Bay and 5 million in Big Bay. The information provided for mortalities was assumed to be around 10% annually for both species. Table 10 resumes this information.

Table 10 – Mussel and oyster production, number of seeds, farm area, seed and harvested shellfish weight.

Shellfish	Parameters	Box 3 (Big Bay)	Box 4 (Small Bay)
Mussel	Farm area (ha)	-	80
	Number of seeds	-	50 million
	Seed weight (g)	-	0,65 g
	Harvested weight (g)	-	25 – 40 g
Oyster	Farm area (ha)	30	15
	Number of seeds	5 million	2 million
	Seed weight (g)	4.3	4,3 g
	Harvested weight (g)	70	70 g

3 Results and Discussion

3.1 Water temperature

Temperature in the Outer Bay is lower than in the remaining boxes, as it is more strongly under the effect of the ocean circulation water. In the Outer Bay the temperature ranges between 11 ºC and 15 ºC. The Big and Small Bay have a maximum of 18 ºC and a minimum 11 ºC. Langebaan has the higher temperatures with a maximum of 20 ºC.

Figure 18 show's temperature stratification during the summer period in all boxes except for boxes 2 and 6, which is in agreement to what has been studied in Monteiro and Largier, (1999). Water temperature in the upper boxes is higher during the summer, lower boxes show higher values during the winter due to the break of the thermocline. Langebaan Lagoon has a more homogeneous water temperature depth profile (less stratification) as the remaining areas. As such, both boxes 2 and 6 have warmer water during the summer and colder in the winter.

The general presence of thermocline during the summer and mixture in the winter in all areas is accordingly to the reality in the bay. The temperature range and the differences between boxes seem also very acceptable.

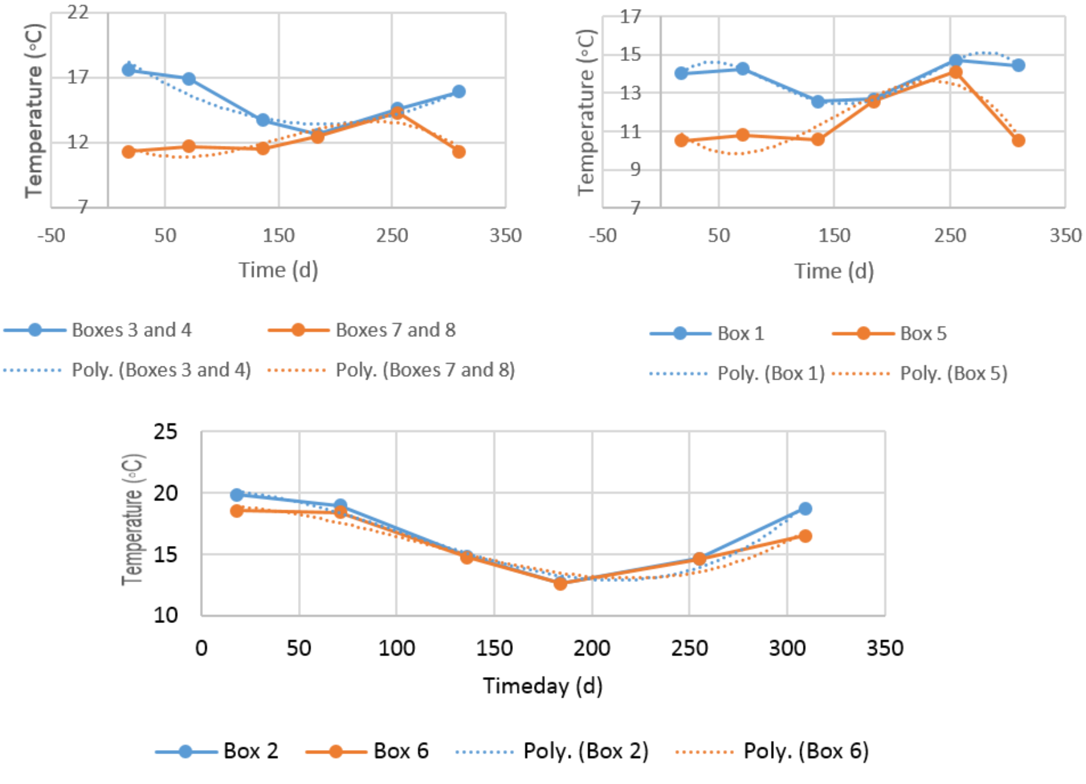


Figure 18 – Temperature results for each box and measured data.

3.2 Salinity

Salinity shows an identical profile in all boxes, the lower values are observed in winter, minimum of 34.7 and a maximum value of 35 psu in the spring. The average salinity is 34.8 psu.

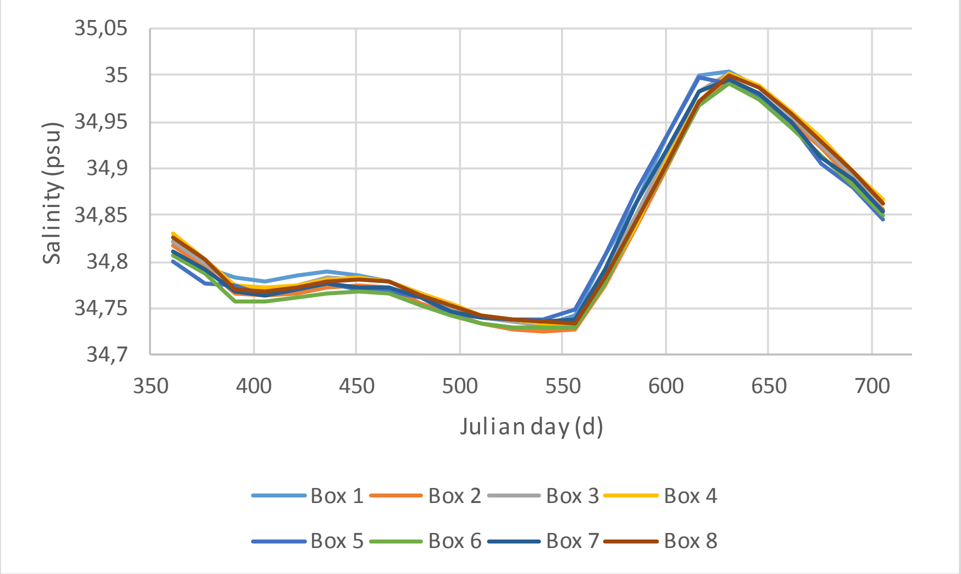


Figure 19 – Salinity results for each box.

Salinity data is available to boxes 1, 3, 5, and 7, therefore, and as all boxes have very similar results respecting salinity, only this boxes were tested. All boxes correlated strongly (r>0.945; v=3) except box 3 (r=0.339; v=3). Even without correlation box 3 had identical mean salinity values (34.80 psu against 34.78 measured) and showed a lower value during winter as measured value, as the remaining boxes did. As a result all boxes seem to have acceptable salinity results.

3.3 Dissolved Inorganic Matter

The nutrient variable used for the phytoplankton growth is dissolved inorganic carbon (DIN), the sum of NO_2, NO_3, and NO_4, as such, these nutrients are analysed as DIN. The results obtained, show a similar profile for all boxes, all boxes have a major peak in the winter with two smaller peaks during summer. The average DIN is 4 µmol L^{-1}, the maximum is 14 µmol L^{-1} and the minimum value is close to 0 µmol L^{-1}. Figure 20 illustrates DIN annual variation.

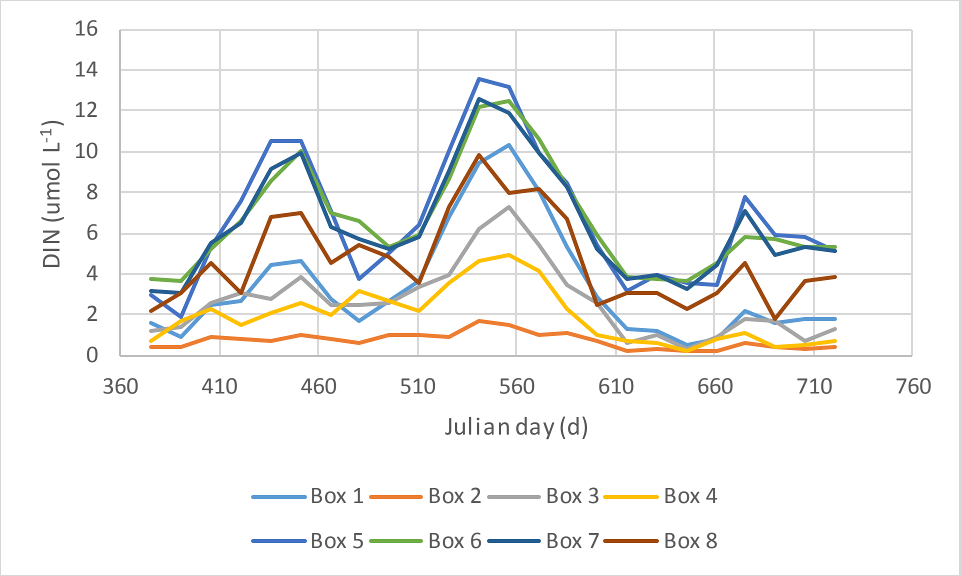


Figure 20 – DIN results for each box.

The only data available to test the nutrient results is the same used to insert them, and therefore in station 1. Most boxes had average annual DIN close to the data used to build the model, except for box 2 which had lower values. Table 11 illustrates the annual average DIN measured and modelled for the different boxes.

Table 11 – Comparison between measured average DIN and mean DIN results for each box.

	Box 1	**Box 2**	**Box 3**	**Box 4**	**Upper layer**	**Box 5**	**Box 6**	**Box 7**	**Box 8**	**Lower layer**
DIN (μg L^{-1})	3.4	0.75	2.63	2.22	2.6	6.5	6.9	6.5	4.9	7.6

Boxes 2 and 6, as expected, have different values from the remaining, because they have a very distinct morphology and a weak connection to the remaining boxes. The observed DIN mean value for each box is not too distant from the measured ones and the spatial variability within the Bay is not known, so this shows only that this values are inside an acceptable range.

DIN may vary substantially and it is difficult to predict, due to the dynamics and communication with the other objects, namely, phytoplankton and POM. These dynamics alter DIN in the water column, which is consumed by phytoplankton and augmented by POM mineralization.

3.4 Phosphate

As observed in figure 21, the 8 boxes have a similar curve for the phosphate concentration. The curve has three peaks: a maximum value in June; an intermediate peak in the autumn; and a smaller one in the spring.

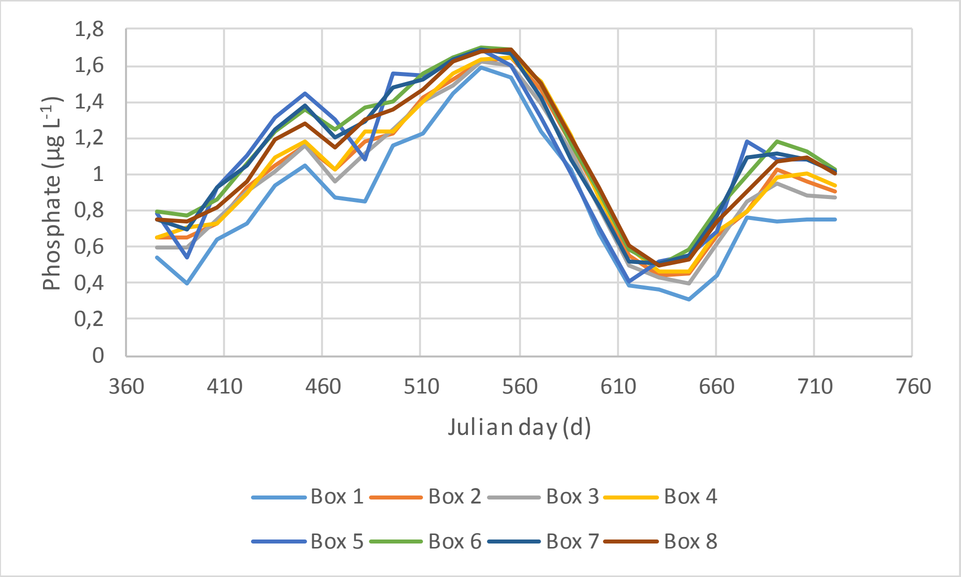


Figure 21 – Phosphate annual results for each box.

The tests made to phosphate are similar to the ones made to DIN (same data source). All upper boxes correlate with measured data (r>0.958; v=4) and none of lower boxes correlates, (r<0.811; v=4). The upper boxes show higher values than the measured ones, about 2 times the measured values. The lower boxes have very similar values to the measured ones. It is difficult to conclude anything besides the average phosphate concentration results are in an acceptable range of values.

Table 12 – Measured average phosphate comparison with mean results phosphate for each box.

	Box 1	**Box 2**	**Box 3**	**Box 4**	**Upper layer**	**Box 5**	**Box 6**	**Box 7**	**Box 8**	**Lower layer**
PO4 (µg L^{-1})	0.84	1.0	1.0	1.0	0.56	1.0	1.1	1.1	1.1	1.2

3.5 Suspended Particulate Matter

The SPM shows a relatively stable evolution across the year, with 4 small peaks occurring approximately every 3 months. The maximum value is 32 mg L^{-1} the minimum 21 mg L^{-1} and the average 26 mg L^{-1}.

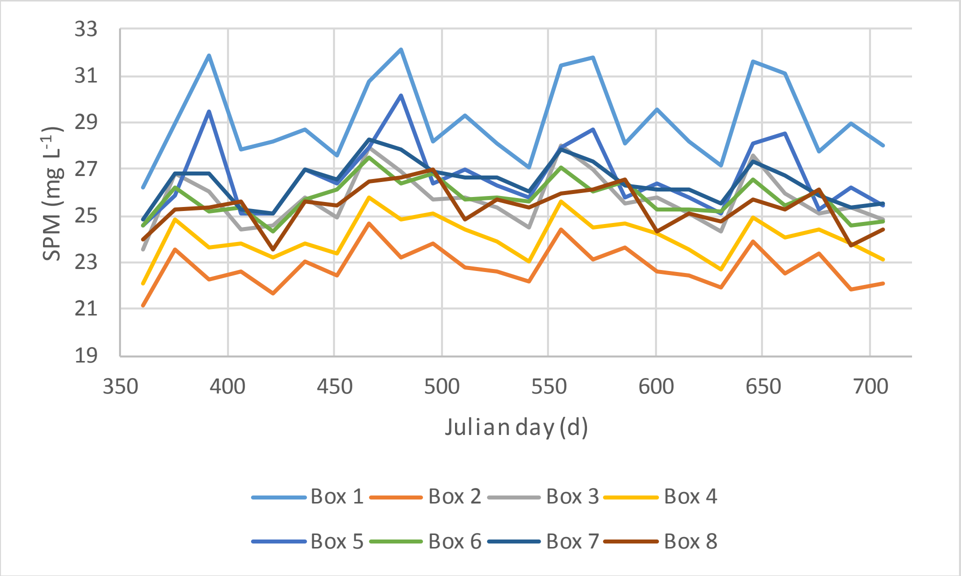


Figure 22 – SPM results for each box.

The only SPM data available is for a 10 day period, which is not sufficient to test SPM. Therefore there can only be commented that SPM results are inside the data range, as the measured range is: 9 to 61 mg L^{-1} and the results range is 21 to 32 mg L^{-1}, which is acceptable.

3.6 Particulate Organic Matter

POM is stable during the year in all boxes. The lower ones show higher and similar values (around 1.8 mg L^{-1}), except for box 5 that has an average value of 1.4 mg L^{-1}. The upper boxes and box 5 have an average value of 1 mg L^{-1}. The Figure below illustrates this.

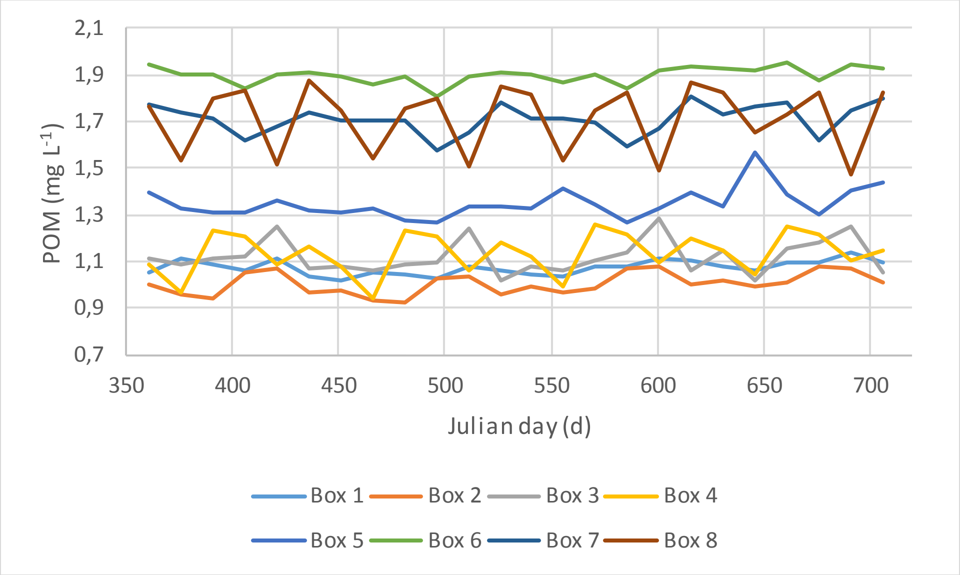


Figure 23 – POM results for each box.

Data available to test POM is the same source as to SPM, with the same limitations. Avvailable data ranges from 0.5 mg L^{-1} to 1.4 mg L^{-1} and the results show values between 0.9 mg L^{-1} and 1.9 mg L^{-1}. POM is influenced by phytoplankton mortalities and by mineralization processes, whereby these parameters adjustment could help to approximate the results to reality. However, the reality will probably differ from the available data, as this is only existing for a short time period.

3.7 Phytoplankton

Phytoplankton biomass, shows major values in September, about 16 µg chl *a* L^{-1}, and a small peak in March. Only box 2 shows a slightly different profile, with higher values during the first months, a major peak during winter and lower values in September. The average biomass is 7.5 µg Chl *a* L^{-1} and the minimum is around 2 µg Chl *a* L^{-1}. Figure 24 illustrates the described annual biomass evolution.

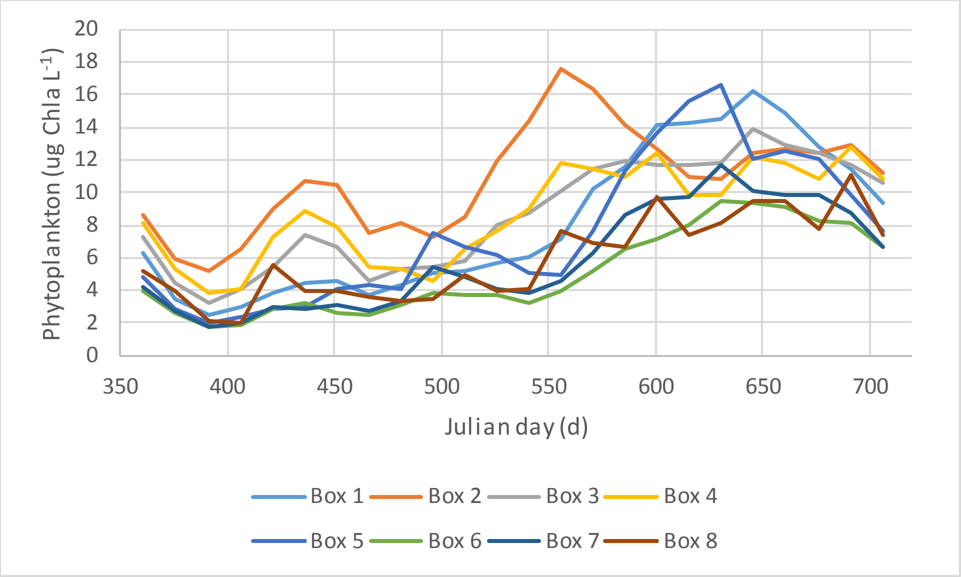


Figure 24 – Phytoplankton results for each box.

Farms are located in boxes 3 and 4 (Big and Small Bay respectively) and therefore is important to analyse them individually. The maximum value is 14 the minimum 3.2 and the average is 8.6 µg Chl *a* L^{-1}. The two boxes have similar curves and values as Figure 25 illustrates.

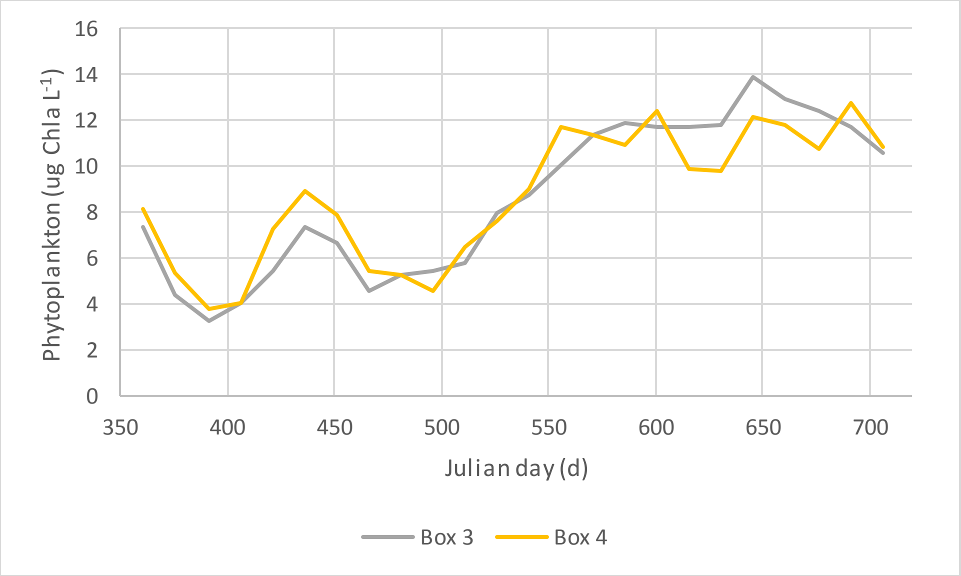


Figure 25 – Phytoplankton results for boxes 3 and 4.

Several studies reported phytoplankton biomass in Saldanha Bay: Henry et al., (1977) and Pitcher et al., (2015) found values between 5 and 32 mg chl *a* m^{-3}, with a mean 15.5 mg chl *a* m^{-3}; Smith and Pitcher, (2015) and Pitcher and Calder, (1998) found a mean value of 8.6 mg chl *a* m^{-3}. Comparing the model results with these studies, they seem to be acceptable, with a mean value of 7.5 mg chl *a* m^{-3}, slightly lower than the results from Smith and Pitcher, (2015) and Pitcher and Calder, (1998).

Smith and Pitcher, (2015) found that the phytoplankton biomass in Saldanha Bays is lower during the winter months, and raises during the summer, with its maximum values in April. As it can be observed in Figure 25, the results for phytoplankton biomass have its minimum in January, a similar depression during the winter months, and a small peak in April, but the maximum biomass happens in September. Pitcher and Calder, (1998), also had two similar peaks: one around April and another around September, although the September peak was not the maximum biomass along the year. Henry et al., (1977) also found a similar profile with one peak in April and another in October.

The phytoplankton biomass results do not correlate with the available measured data, despite this the curve profile is similar to the measured studies, showing the same cyclic peaks and depressions. The total average chlorophyll in the data used to build the model is very close to the one in results with a mean 7.8 mg chl *a* m^{-3}.

The phytoplankton biomass correlates strongly for the same boxes ($r>0.919$; $v=3$) with boundary values. Meaning that most of phytoplankton biomass in the model comes from the ocean, as opposite to primary production inside of it.

3.8 Ecological model discussion

Phytoplankton biomass in the Bay is mostly limited by nutrients and light (Pitcher et al 1992). The model is not completely accordingly to the reality, as phytoplankton seems to be mostly dependent on exchanges with the boundaries, which happens mostly because of the system morphology. This system parcelling in 8 big boxes simplifies much of the spatial variation, meaning that at a given moment the value of each variable is homogeneous inside each box. This will approximate the boundary effects on the more remote areas of the Bay, as the transport time between these boxes and the boundary is shorter, and the maximum distance between them is one of 2 boxes (for Langebaan area in particular). This explains why the variables correlate with the boundary conditions more than with collected data, as its influence augmented with this morphology.

It is difficult to evaluate whether the model describes the main ecological processes properly, as the available data are not collected for this study and leave some uncertainty about their accuracy for this study. However the results produced are within the range of expected values for all the variables and show some acceptable temporal distribution. Most importantly the phytoplankton results have an appropriate range of values and a profile that fits in the measured reality.

The absence of specific parameters for the relation of these variables, such as, the maximum growth rate and optimum light for phytoplankton and the mineralization rates for POM, give some room for adjustments.

3.9 Model validation – Standard Scenario

Estimated harvest is based on information provided by local farmers, mostly based on simple estimations, the model was calibrated in order to obtain harvest results close to this estimations. Estimated mussel production in Saldanha is about 2400 tonnes, the modelled harvest results have approximately the same values. The oyster estimated production was about 520 tonnes for Big Bay and 150 for Small Bay. The modelled results for oyster harvest are 510 tonnes for Big Bay and 140 tonnes for Small Bay. Table 13 summarizes the expected and modelled harvest for each box.

Table 13 – Modelled and estimated production for each box, organized in species.

		Box 3	**Box 4**
Mussel annual production (ton)	Estimated	-	2400
	Modelled	-	2400
Oyster annual production (ton)	Estimated	520	150
	Modelled	510	140

Figure 26 shows the annual mussel and oyster harvest during 10 years of cultivation. The first harvest year for mussels is year 3 with about 1700 tonnes, stabilizing in a mean 2400 tonnes on the third harvested year. Oyster harvest starts in year 2 and it stabelizes in the second harvested year (year 3) for both boxes. Box 3 produces considerably more as the number of seeds in it is about 2.5 times bigger.

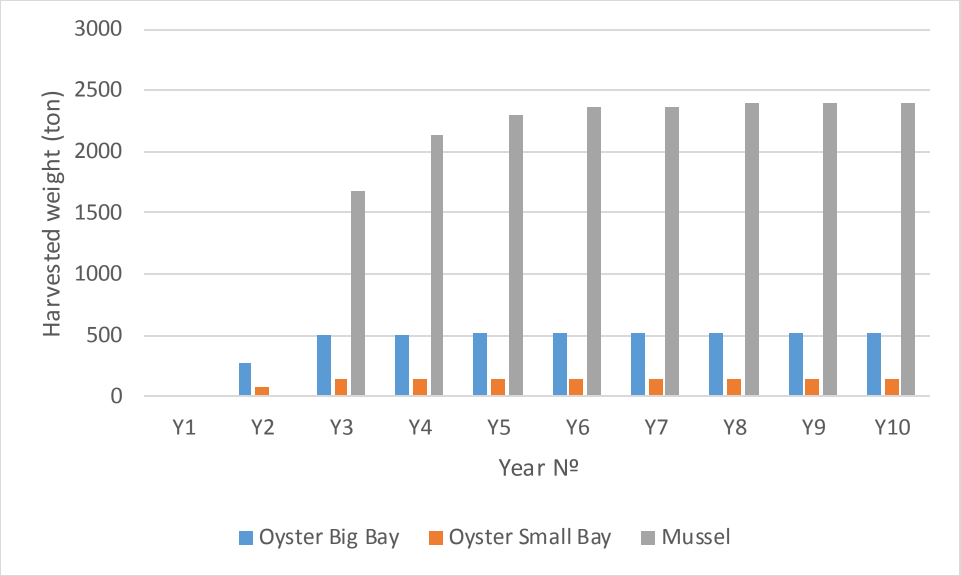


Figure 26 – Standard scenario harvested weight for each species for each area

Figure 27 shows the oyster individual weight in Winshell during one year (two charts on top) and mussel individual weight (the one on the bottom). Box 4 produced bigger oysters, with 130 g and 125 g in box 3. Mussel individual weight was around 37 g after 13 months.

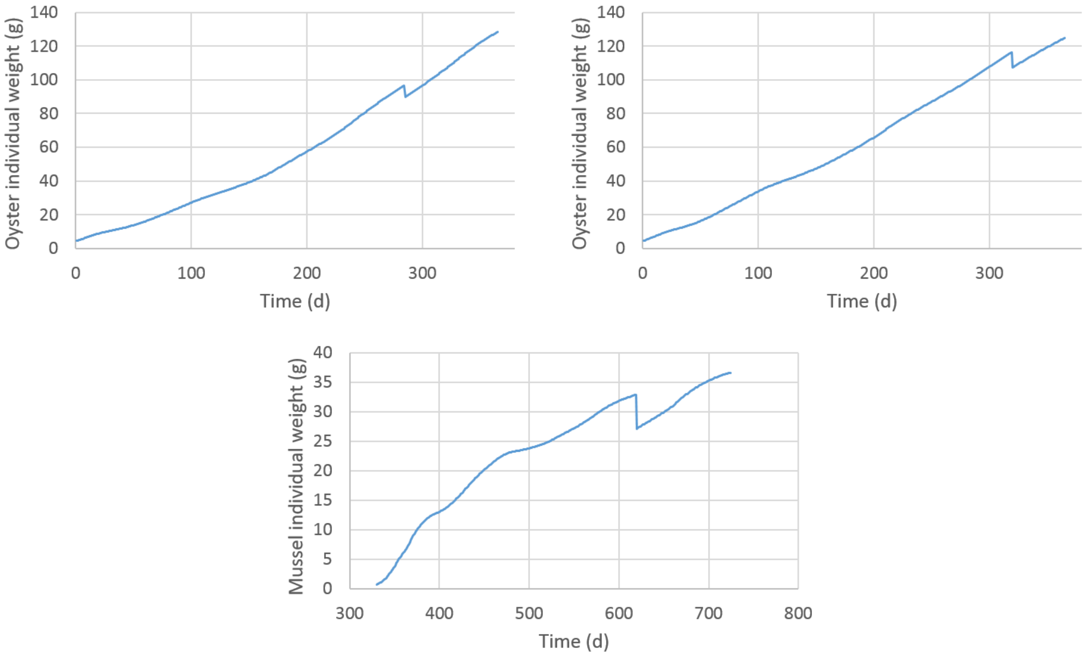


Figure 27 – Oyster individual weight evolution in box 3 (left side) box 4 (right side), mussel individual weight evolution in box 4 (bottom)

Mussels individual weight is within the local farmers estimations: between 25 and 40 g; Oyster individual weight is much above the estimated mean 80 g, about 30 g above it. Data introduced in Winshell relative to Small Bay, was sligthtly higher in phytoplakton biomass compared to Big Bay and therefore has heavier results.

Winshell does not considerate competition nor any group dynamics inside the box. Therefore, the smaller dymensions and higher seeding in Small Bay facing Big Bay are not considered in Winshell. Winshell results are merely used to test if the conditions inside the Bay alow the shellfish to grow to the expected individual weight.

The change of a parameter such as POM mineralization may have substantial effects on the bivalve growth rates in Winshell. The sensitivity analysis below (Figure 28) shows the variation in mussel growth, the standard model with a mean POM concentration of 1.1 mg L^{-1}, case 1 with 1.3 mg L^{-1} and case 3 with 0.9 mg L^{-1}. This shows how a small variation of 0.2 mg L^{-1} in the mean POM concentration can change the final weight with almost 20 g. Further calibration could approximate the modelled individual weight to the real values.

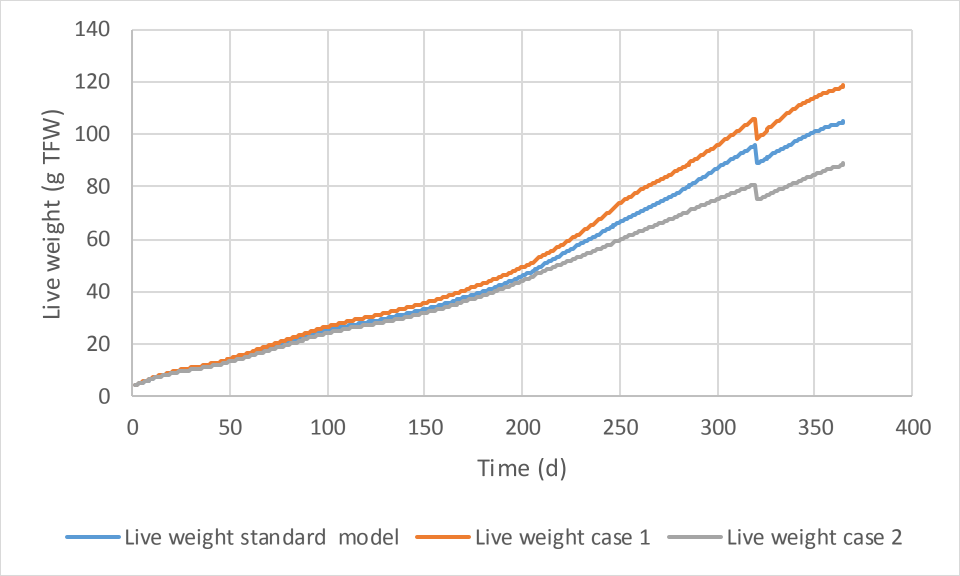


Figure 28 – Oyster individual weight for 3 different POM scenarios: standard model (mean 1.1 mg L^{-1} POM); case 1 (mean 1.3 mg L^{-1} POM); case 2 (mean 0.9 mg L^{-1}).

Winshell estimates system main uptakes and intakes. As the Table 13 illustrates, oyster production removes about 1 tonnes Chla from the Bay per year as the mussel production removes circa 38 tonnes. Oyster production removes 106 tonnes POM per annum, circa 46 tonnes through biodeposition, mussel production removes circa 6500 tonnes POM per annum, about half of it by biodeposition. Oyster production removes circa 3 tonnes nitrogen per annum, and mussel production removes circa 125 tonnes nitrogen.

Table 14 – Bivalve ecosystem removals for each farmed box.

	Box 3	**Box 4**		**Total oyster**	**Total**
	Oyster	Mussel	Oyster		
Phytoplankton (ton)	0.70	37.74	0.24	0.94	38.68
POM (ton)	106.0	6459.07	38.72	144.80	6603.87
POM Biodeposition (ton)	45.7	3399.17	17.12	62.84	3462.02
N (ton)	2.30	124.93	0.81	3.11	128.03

Mussel are responsible for about 99% of the calculated aquaculture removals in Saldanha Bay for the referred parameters, this not only due to the higher mussel harvested weight. Considering the removal per harvested weight, mussels remove circa 11 times more phytoplankton POM and N as oysters do.

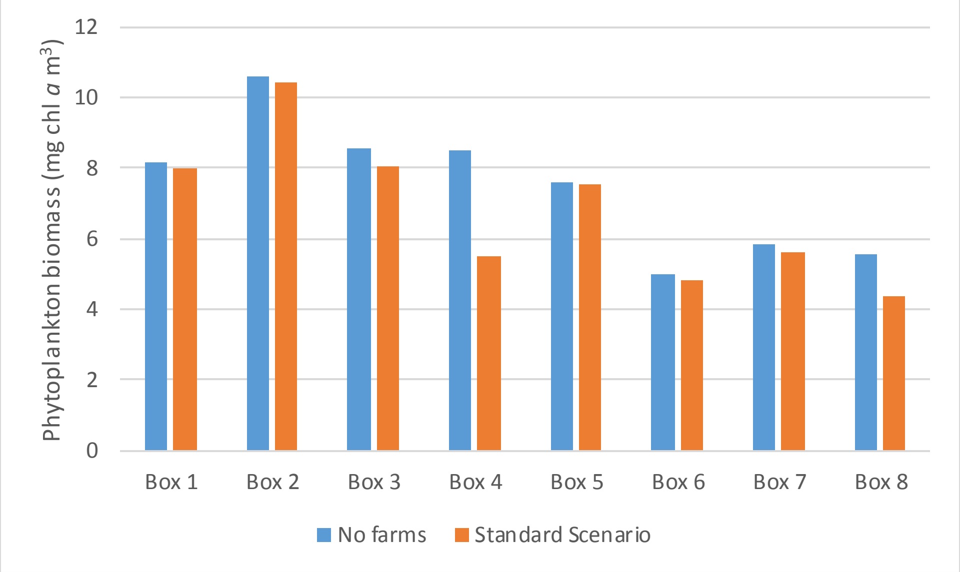


Figure 29 – Difference between phytoplankton biomass before and after adding shellfish farms to the model.

The introduction of shellfish into the model impacts the phytoplankton biomass, Figure 29 shows the phytoplankton biomass results for each box before and after the farms introduction. The boxes in which the difference is bigger are 4 and 8, followed by boxes 3 and 7. The impact in the remaining boxes was not significant. The average phytoplankton biomass difference in box 4 is 3 mg chl *a* m^{-3}, in box 8 1.2 mg chl *a* m^{-3}, in box 1 only 0.5 mg chl *a* m^{-3} and in box 7 0.2 mg chl *a* m^{-3}.

Farms are located in boxes 3 and 4, but box 3 is about 3 times bigger in volume, and box 4 has about 80% of the production. Box 4 is then submitted to a much bigger pressure than box 3 is. This explains why the insertion of farms has greater impacts on phytoplankton biomass in box 4 and box 8 which is beneath it.

Table 15 – Mean phytoplankton comparison, before and after adding the farms into the model, in boxes 3, 4, 7, and 8.

	Box 3	**Box 4**	**Box 7**	**Box 8**
Before farms **(mg chl *a* m^{-3})**	8.57	8.52	5.82	5,56
After Farms (mg chl *a* m^{-3})	8.05	5.48	5.60	4.34
Difference (mg chl *a* m^{-3})	0.52	3.03	0.23	1.22

Table 14 illustrates the differences between the average phytoplankton biomass before and after introducing the farms. As most of the analysed studies such as Pitcher et al. (2015), Pitcher and Calder (1998), and Smith and Pitcher (2015) were made under the farms pressure on phytoplankton, these values must match the measured ones. Pitcher and Calder, (1998) found lower biomass in Small Bay, so the major difference obtained for these boxes is an expected result.

The model allows to observe the farms influence in the ecosystem. Using Winshell individual removals it is possible to make an estimation of the ecosystem services and some possible impacts crated by the actual farming intensity. The current aquaculture activities may remove about 38 tonnes chlorophyll a, 126 tonnes nitrogen and 6500 tonnes POM. This improves water quality and compensates for human nutrient inputs. Considering an annual emission of about 5 kg N per capita (J and Drecht, 2004), and the populations of 21600 people of Saldanha and 8 000 in Langebaan, this would represent an annual discharge of 148 tonnes N into the Bay and lagoon area. The present seeding intensity potentially removes about 85% of human nitrogen water inputs. Table 16 illustrates the total removals by each species.

Table 16 – Total scenario removal for each species and total

	Mussels	**Oysters**	**Total**
Phytoplankton Removal (ton)	37	1	38
Nitrogen removal (ton)	123	3	126
Water clearance (m^3)	$6.02*10^9$	$1.29*10^8$	$6.15*10^9$
POM removal (ton)	6353	145	6497
POM biodeposition (ton)	3344	63	3406

3.10 Carrying capacity

3.10.1 Production carrying capacity

Saldanha's Bay production carrying capacity is the maximum production that could be sustained by the Bay. Using the interest of local scientists and farmers in production inside Small Bay, production carrying capacity was determined for Small and Big Bay individually. Due to the morphology of the Bay, and especially the model's morphology, production in the Big Bay influences significantly the food availability in Small Bay.

3.10.1.1 Small Bay

The production carrying capacity for Small Bay was calculated by maximizing the seeding for both mussel and oyster individually. For both scenarios the remaining farms in Small and Big Bay were not altered from the standard scenario seeding. Figure 30 illustrates the harvest obtained for different seed intensities. The maximum production for mussel is about 5000 tonnes live weight with seeding of about 145 tonnes. Oyster maximum production is about 20000 tonnes live weight, with seeding of about 1100 tonnes. The Bay carrying capacity for oyster production is considerably higher as for mussel, about the quadruple.

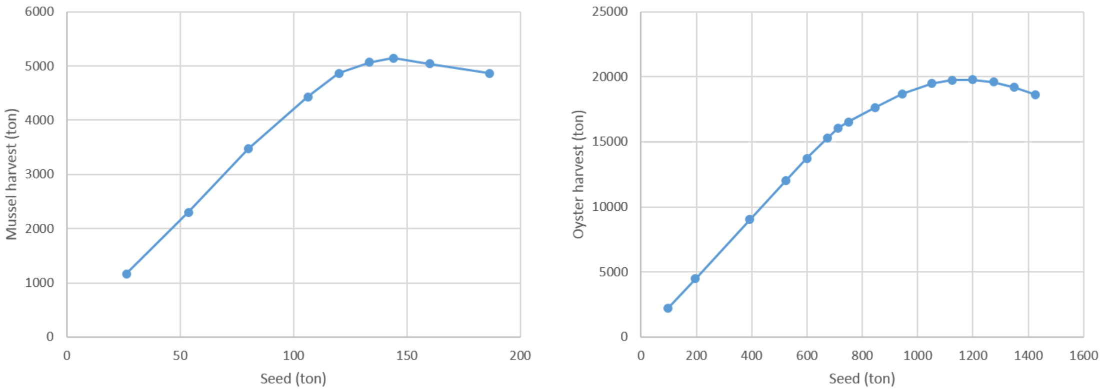


Figure 30 – Harvest results for different seeding intensities of mussel (left) and oyster (right), inside Small Bay

Seeds have different weight for the two species: the oyster is assumed to be 4.3 g and the mussel 0.65 g. Therefore, although the seeded oyster weight is superior, this is not directly comparable. As Figure 31 shows, the number of seeds supported to obtain the maximum production in Small Bay is also higher for oyster production.

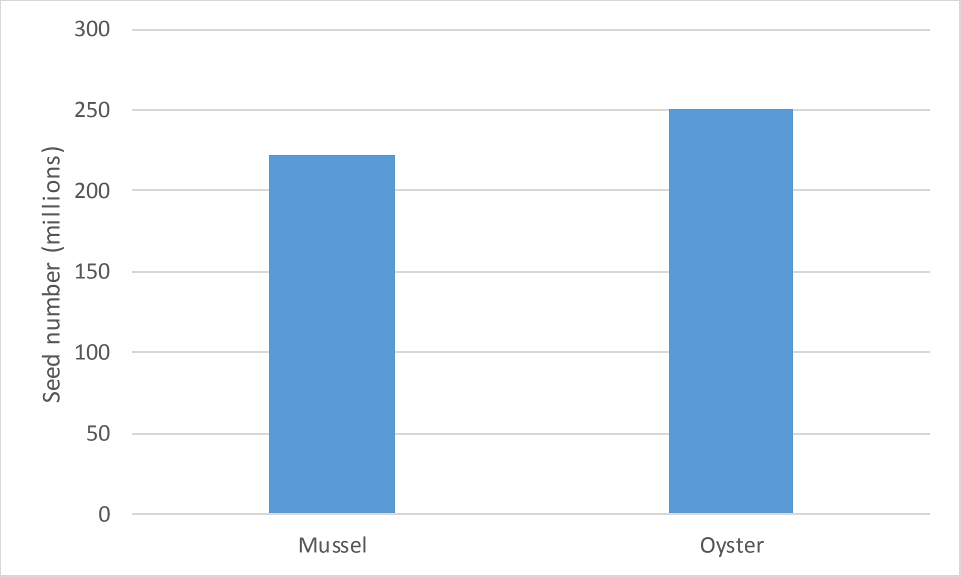


Figure 31 – Number of seeds in Small Bay for the two maximum scenarios

Although oyster production is considerably higher than mussel production, in terms of meat production they are not directly comparable. Oysters have big and heavy shells which constitute about 70% of its live weight and mussels a smaller shell which represents only 40% of its live weight. These estimations were carried out using Winshell average wet meat and shell weight during the growth process of both species. As Figure 32 illustrates, oyster wet meat weight for this scenario would be about 6000 tonnes and mussel would be about 3000 tonnes. Then the maximum possible meat production would be achieved with oyster farms.

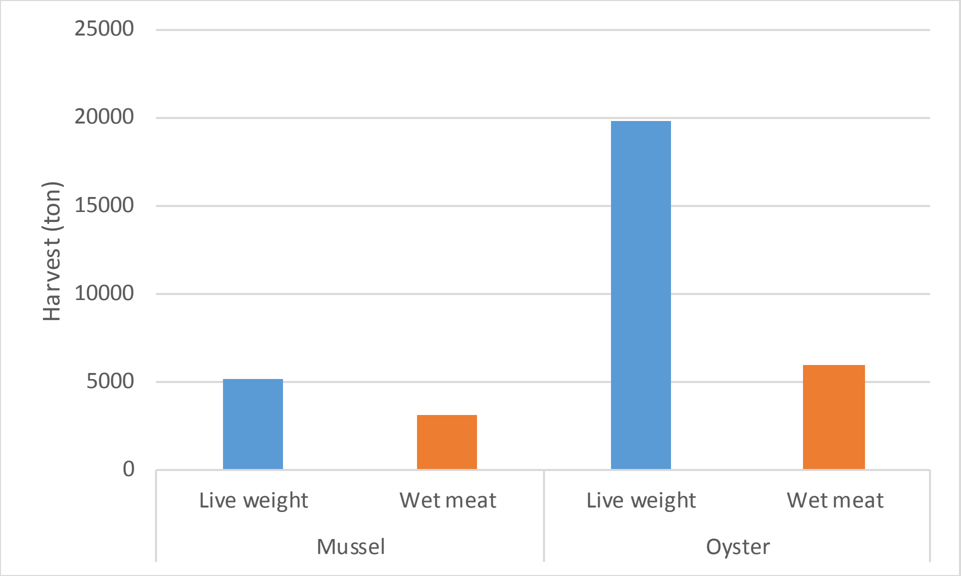


Figure 32 – Harvested shellfish in live weight and wet meat in tonnes for the maximum production scenarios in Small Bay

The maximum production capacity, normally, is not the most profitable scenario. Harvested shellfish have in this conditions lower growth rates and smaller shellfish have lower market value. Higher seeding intensity have higher costs associated with seed purchase and farm maintenance (Ferreira et al., 2007). Therefore the maximum production scenario is normally not the most interesting one for farmers.

3.10.1.2 Big Bay

Big Bay maximum production capacity for oyster production was calculated similarly to Small Bay. The seeding intensity was gradually raised in this box, and the remaining farms (in Small Bay) were kept in the standard scenario level. As Figure 33 illustrates, the maximum production for this Bay would be 100000 tonnes, with a seeded weight of about 4500 tonnes.

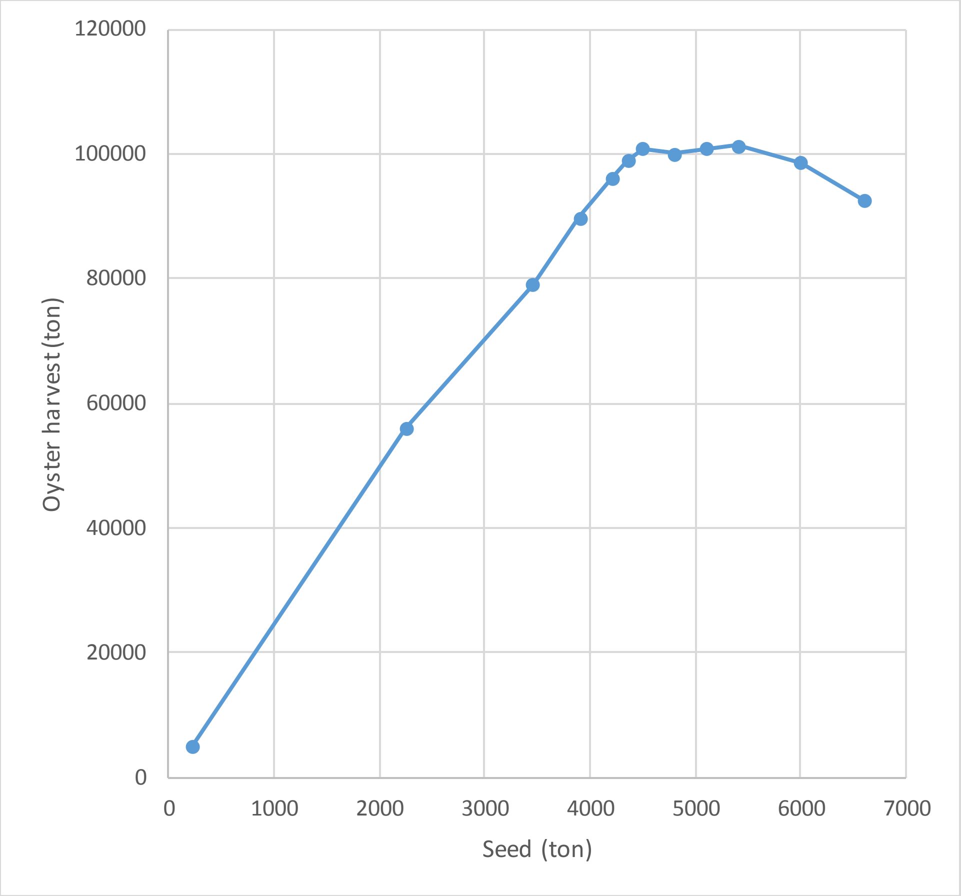


Figure 33 – Oyster harvested weight per seeded weight inside Big Bay

Determined oyster production capacity for Big Bay is compared with the oyster production capacity for Small Bay in Figure 34. Calculated production capacity is circa 5 times higher in Big Bay than in Small Bay. Big Bay is about 3 times bigger in area, so it would be expected to have a higher capacity.

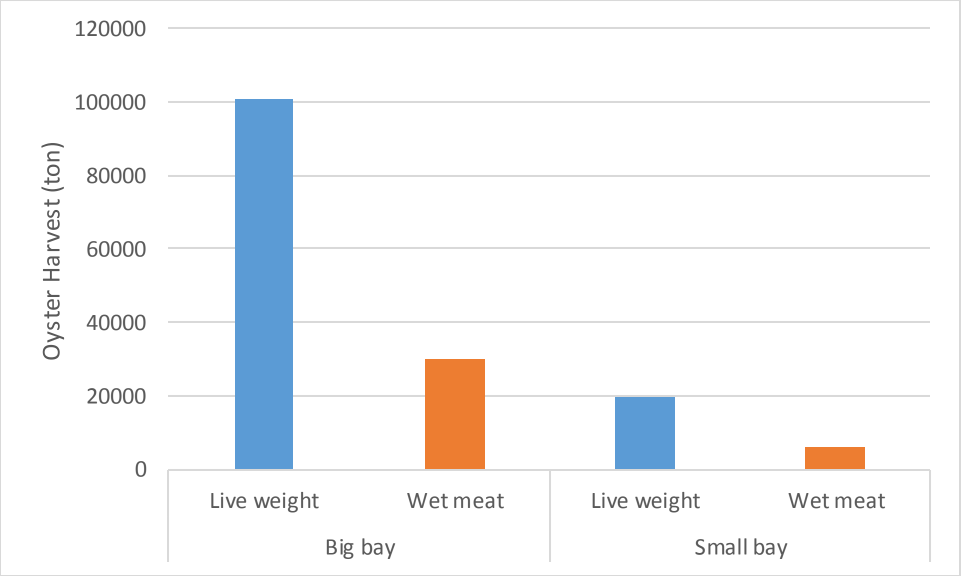


Figure 34 – Comparison of harvested live and wet meat weight of oyster in Small and in Big Bay.

3.10.1.3 Small and Big Bay comparison

Small Bay production carrying capacity scenario would have significant impacts in phytoplankton availability. As Figure 35 shows, phytoplankton biomass compared to standard scenario is considerably lower in boxes 4 and 8, and almost unchanged for the remaining. Box 4 and 8 have an average 2.5 and 3 mg chl *a* m^{-3}, respectively.

The Big Bay production carrying capacity scenario would affect the entire Bay's phytoplankton availability. This is an expected output since this scenario introduces about the quadruple shellfish inside the Bay and, as a consequence, has more phytoplankton uptake.

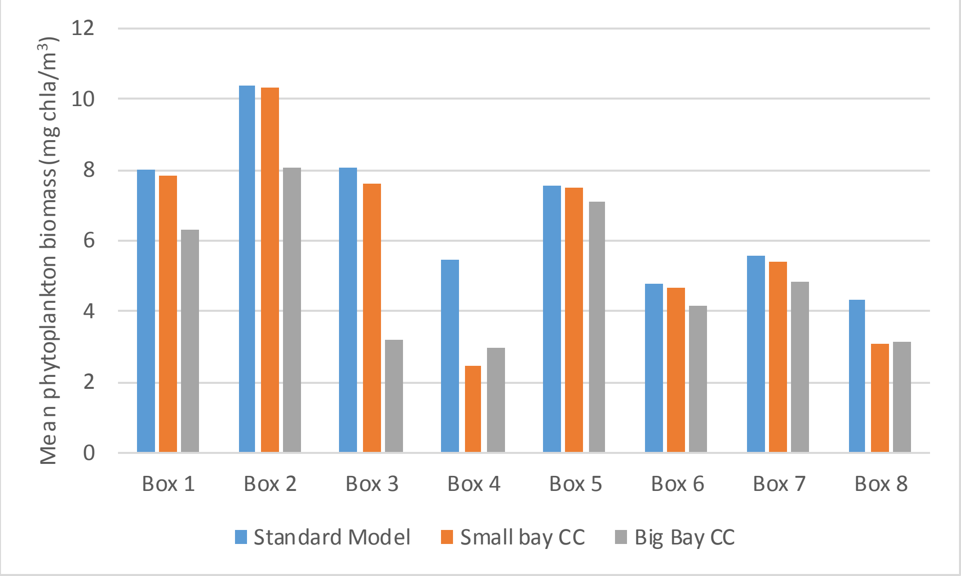


Figure 35 – Average phytoplankton biomass inside each box

When the two studied carrying capacity scenarios seeding intensities are used simultaneously, the total harvested shellfish is less than the total obtained with Big Bay maximum production carrying capacity alone.

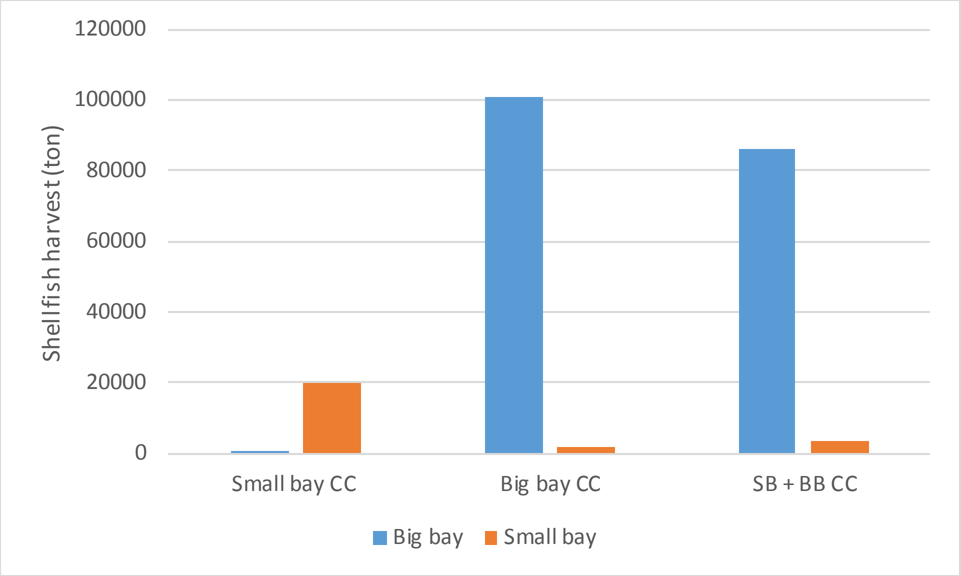


Figure 36 – Comparison of maximum production capacity in each box

3.11 Production scenarios:

After questioning local farmers and scientists, it was concluded that there is a bigger interest in expand the cultures in Small Bay both for mussels and oyster. Therefore, two scenarios were built and analysed for Small Bay: one increasing oyster production; and another mussel production.

3.11.1 Scenario 1

In this scenario the oyster seeding remained the same as in standard scenario, and the mussel seeding was raised to a number 2 times bigger. In this scenario, the oyster production was not affected by the mussel seeding raise and the mussel production stabilized with circa 5100 tonnes per annum. The chart below shows this scenario harvest during the first 10 years.

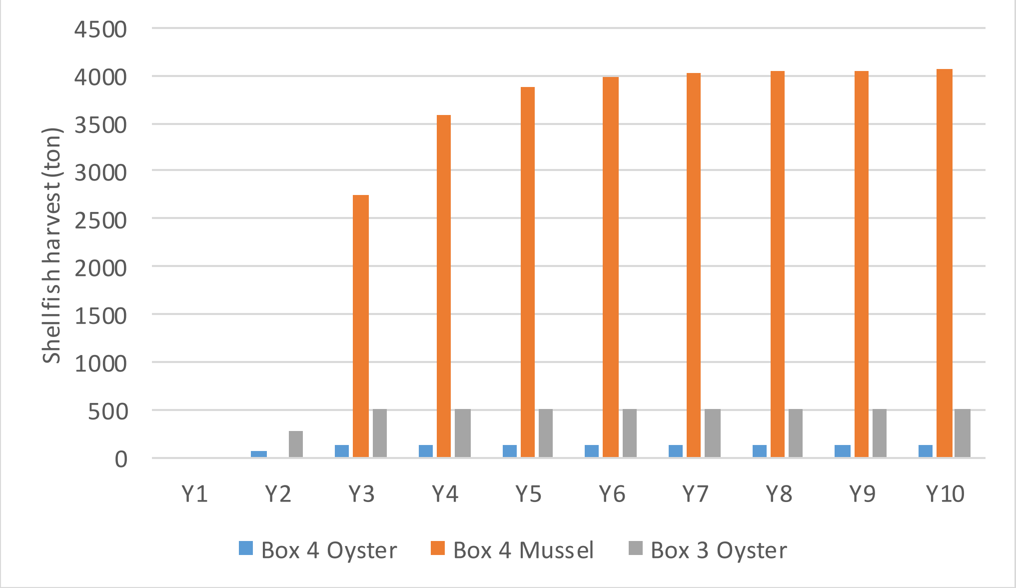


Figure 37 – Scenario 2 annual shellfish harvest.

3.11.2 Scenario 2

Oyster seeding in the Small Bay was raised to a number 100 times bigger as in standard scenario, the oyster seeding in Big Bay and the mussel seeding was kept at the same intensity as in the reference values. Oyster harvest in Big Bay was the same as in standard scenario, and the mussel production diminished from 2400 tonnes to 2100. The oyster harvest in Small Bay raised to 14000 tonnes per year, as the chart below illustrates. The seeding intensity was raised till obtain a similar chlorophyll profile.

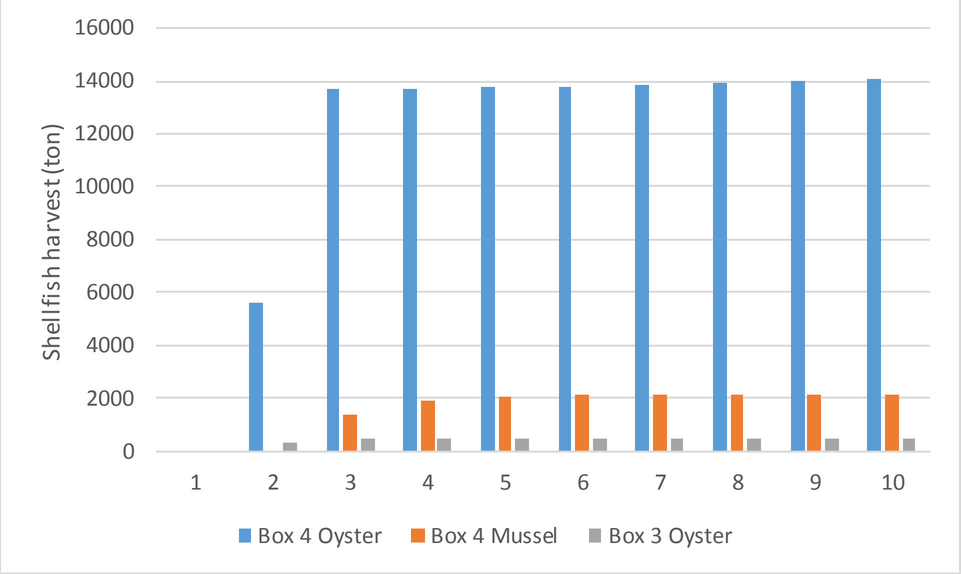


Figure 38 – Scenario 2 oyster annual harvest in box 4.

3.11.3 Ecological impacts – Scenario 1 and 2

The two scenarios have very similar phytoplankton biomass distribution. A significant difference in phytoplankton is observed in boxes 4 and 8, compared with the standard scenario. The chart below illustrates this difference. The mean chlorophyll concentration during one year in box 4 is 37% lower than the standard scenario and in box 8, 19% lower. The remaining boxes have no significant differences.

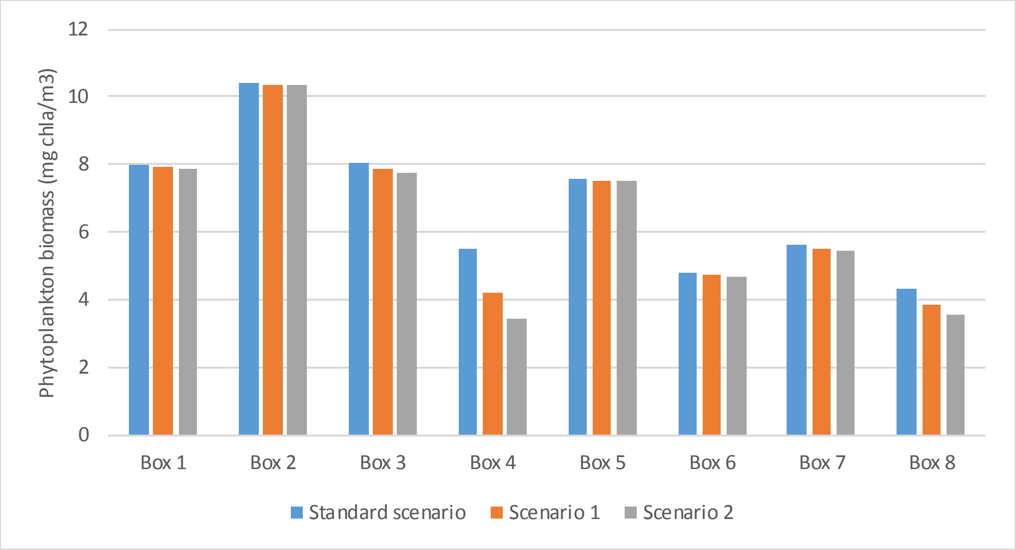


Figure 39 – Average phytoplankton biomass for each box and each scenario

Shellfish production in this scenarios would have great impacts on the water column. Accordingly to WinShell results, scenario 1 would result in remoting circa 94 ton chl *a* from the water column per year, circa 310 ton N and circa 16000 ton POM. Table 17 summarizes this information.

Table 17 – Scenario 4 ecological removals for each shellfish species.

	Scenario 1	**Scenario 2**
Phytoplankton Removal (ton)	94	65
Nitrogen removal (ton)	310	216
Water clearance (m^3)	$1.5 * 10^{10}$	$9.8 * 10^{9}$
POM removal (ton)	16027	10635
POM biodeposition (ton)	8421	5189

3.12 Scenario discussion

Shellfish aquaculture may have positive effects in the Bay's ecosystem when seeded in the correct intensity. These removals may have an important role in compensating the nutrient inputs coming from growth in waste water discharges, which is happening due to the population growth in Saldanha and Langebaan. This top down control may be very important in preventing toxic algal blooms, which benefits both aquaculture and fishing industry. Besides this, the phytoplankton depletion will increase the underwater light availability, promoting the development of submerged aquatic vegetation, which are important nursery sites for fish.

Biodeposition impacts over the farms may be significant in certain conditions, but this could only be analysed at a farm scale with a different program. Further research and object development would be necessary to observe the concrete impacts of different seeding intensities in the wild shellfish species. The acceptable limit to ecological impact created by this activities is set by local stakeholders and, therefore, may vary from site to site. The calculated maximum production scenarios would most probably have considerable effects in the wild species by food competition, since Sequeira et al., (2008) suggest that over-seeding may affect the benthic biodiversity through food competition. This two scenarios result in a big reduction of phytoplankton biomass in the water column. The oyster production involves seed purchase, and as such, the decrease in harvest per seed weight is economically impacting for the farmers.

Scenarios 1 and 2 are interesting for farmers in Small Bay, as the production is increased without significantly affecting bivalve growth rates. For the ecological perspective it is difficult to analyse at what point the chlorophyll depletion would affect the wild filter feeders, without a previous study to determine the wild life abundance, diversity and needs. Considering that farmed bivalves growth rates are not significantly affected and that phytoplankton biomass decrease is lower in box 8 (where the wild species would locate) it is reasonable to assume that the wild species production would not be prejudiced.

The scenarios within this model give a system scale perspective, at which the competition for food inside the farms is not considered, what may overestimate the results. For such detailed analysis the use of another program such FARM would give a more local perspective. The exclusion of the wild species competition may also condition the results and over-estimate the farms harvest. Despite this the account for wild species would involve a different calibration of the ecological model, and could still have similar results. Considering the uncertainty about most of the parameters used in the ecological model, the use of different ones to consider these species would be perfectly valid, and would probably be more close to the reality, since these animals are part of the real ecosystem.

Scenario 2 production could present a sales volume of about 12 million euros. Which could have positive social impacts in the community. According to Olivier et al., (2013) there is a relation of 89 employees for each 1000 tonnes shellfish produced. Which means this level of production could employ 890 people, about 600 more people (assuming that now there are about 290 people employed in the area, accordingly to the ratio).

In a future perspective, farmers could consider to participate in the nutrient credit trading market. Given the potential removal of circa 310 ton N of scenario 1, this could represent an annual income between 3 and 86 million euros, according to the tabled costs. These revenue represents between 20 and 670% of the estimated sales volume, a significant amount for the farmers. Further analysis would have to be carried out to determine whether there would be any use conflicts, or impacts in local activities such fisheries, this could affect both social and physical carrying capacity, and could determine a lower carrying capacity for the Bay.

4 Conclusion

This study main objectives were to: (1) describe Saldanha's Bay main environmental variables and its interaction with an aquaculture sector; (2) create different production scenarios; (3) determine the system carrying capacity for shellfish production; and (4) to create a useful tool for managing the Bay.

Saldanha Bay is a sheltered ecosystem northern from Cape Town in South Africa. This Bay is part of the Benguela upwelling current system, providing a productive environment, with excellent conditions for bivalve production. This system is home for several oyster and mussel farms, with a total annual production of about 3000 tonnes.

This study made use of EcoWin, an object oriented program developed for modelling processes in aquatic systems. The model incorporates a previously developed hydrodynamic model with a biochemical model developed for northern Ireland, Belfast lough, in Ferreira et al. (2008). The biochemical model was adapted for Saldanha Bay, using data collected by Probyn (Monteiro and Largier, 1999; Smith and Pitcher, 2015). This system model includes many variables such as, dissolved nutrients, particulate suspended matter, phytoplankton, shellfish, Man interaction, light, salinity and water temperature. The farm component was developed using production methods and other information provided by local producers after contacted.

The variables are dynamic and communicate with each other. Phytoplankton consumes nutrients, and, through mortality, transforms into particle matter. Particulate organic matter decomposes into nutrients. Shellfish consume both particulate organic matter and phytoplankton, they are also harvested and seeded by Man object. Salinity, light and temperature influence way other variables interact and its growth rates.

The model uses an 8 box system connected to the ocean, its only boundary. The biochemical model uses suspended particulate matter, dissolved nutrients, salinity, all forced in the boundary. Water temperature and light were forced for the entire system.

The results for all ecological variables are inside the respective, acceptable range of values. Mean phytoplankton biomass is 7.5 mg chl *a* L^{-1}, describing a curve with one major peak in September and a smaller one in March. This against 8.6 mg chl *a* L^{-1} studied mean biomass is an acceptable value.

After the addition of shellfish into the model, the phytoplankton biomass results kept an acceptable mean 7 mg chl *a* L^{-1}, with a biggest difference in box 4, where the most farms are located. Pitcher and Calder, (1998) results show a lower phytoplankton biomass in Small Bay, which means the lower values determined after introduction of shellfish area are adequate to the reality.

The model simulates oyster growth with an average weight of 120 g and mussel with 35 g. The annual harvest results are identical to the actual production, with a 2400 ton mussels and 140 ton oyster in Small Bay, and about 510 tonnes in Big Bay. The oysters grow till 120 g in 365 days as mussels reach 35 g in 395 days. The individual growth was much higher than the expected results, which could be altered with further calibration of the model.

Production carrying capacity was determined individually for the Small Bay and Big Bay areas. The Small Bay area had a maximum production capacity of about 5000 ton harvest for mussel alone and 20000 tonnes for oyster alone. Big Bay area had the biggest production with about 100 000 ton oyster harvest. All the 3 scenarios were built from the standard scenario by raising seeding intensities. These three scenarios were considered economically detrimental as it would influence the shellfish size, lowering its market value. It is also not detrimental from the environmental perspective, as it would probably also influence wild species growth result in phytoplankton depletion, most likely impacting the wild bivalve species population inside the affected areas.

The contacted local farmers showed interest in increasing production inside Small Bay and therefore two scenarios were built. Scenario 1 raised mussel production and scenario 2 oyster production, both inside Small Bay. Both scenario 1 and 2 raised the seeding intensity in Small Bay comparing with standard model. Scenario 1 raised mussel production up to 5100 tonnes, and scenario 2 raised oyster production up to 20 000 tonnes. These scenarios showed great economic and environmental potential. The possible environmental impacts in the benthic community do not seem to be significant, and there are several potential positive impacts: light availability to benthic communities, toxic algal bloom prevention and nutrient removal.

This study accomplished all of its objectives, as it produced a model that successfully describes the ecosystem main interactions, capable of simulating the ecosystem response to different inputs. It produced several production scenarios and determined the carrying capacity for bivalve production in the Bay. This model is a very powerful management tool, which can be used by local decision makers to maximize the Bay social, economic and environmental components of Saldanha Bay.

The academic nature of this work influenced availability of some resources, which could potentiate the accuracy and value of the model to a higher level. The model was built using available work, which did not cover for all the wanted accuracy.

The hydrodynamic model for this kind of study would ideally have a finer grid, providing a more detailed spatial distribution and extra accuracy to the information produced. However, this model had to be adapted from its original one year long construction to a less detailed 3 months long one, being then used for simulating a one year period, losing some detail in the water circulation.

Data used was not collected with the purpose to be used in this study and therefore, for some variables, the information available did not cover for the exact areas where it should. So, data was adapted for the model requirements but did not achieve a desirable high accuracy level. Despite this, data available was sufficient to build a strong analysis. The parameters used for ecological processes were adapted from studies produced for other sites, since there were no studies for Saldanha Bay specifically, which could also add strength to the model results if determined and studied for this particular case.

For future developments, there are some aspects that could be developed and make this work more valuable. It would be very interesting to integrate this work in a bigger project, where data was collected for boundary conditions on particles, phytoplankton and nutrients, as for the temperature in each box. It could also be included the development of the hydrodynamic model in a finer grid and extent it to full year coverage, which would add some extra detail in spatial distribution.

This study could also be enriched with the introduction of a wild zoobenthos component. This would include the competition and interaction of wild species with the ecological variables, would add some strength to the model, a more complete description of the ecosystem, and allow the analysis of the impacts on the benthic environment, with which the farmed bivalves compete for food.

The addition of zooplankton would also make this model stronger and allow an indirect analysis of the impacts of aquaculture to higher trophic animals in the ecosystem. Zooplankton feds on phytoplankton and is food for some fishes and higher trophic animals. As such depletion of zooplankton can have high impacts on higher trophic fish and, consequently, the fishing industry. This would also be a very interesting and more complete analysis to the ecological carrying capacity of bivalve production in the Bay.

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