# Spatial Planning and Bio-Economic Analysis for Offshore Shrimp Aquaculture in Northwestern Mexico

**Bren School of Environmental Science & Management**
**University of California, Santa Barbara**
**A group project submitted in partial satisfaction of the degree requirements for the Master of Environmental Science & Management**

**Team Members**
**Michaela Clemence | Frank Hurd | Heather Lahr | Asma Mahdi | Audrey Tresham | Jeff Young**

**Faculty Advisor**
**Steve Gaines**

**March 2011**

# Spatial Planning and Bio-Economic Analysis for Offshore Shrimp Aquaculture in Northwestern Mexico

As authors of this Group Project report, we are proud to archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

Michaela Clemence

Frank Hurd

Heather Lahr

Asma Mahdi

Audrey Tresham

Jeff Young

The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Steve Gaines, Advisor and Dean

March 2011

## Acknowledgements

We extend our most sincere thanks to everyone who helped make this project a success. We would especially like to thank our advisor, **Steve Gaines**, whose insight and support was integral in guiding us through this process, as well as our external advisory team: **Chris Costello**, **Sarah Lester**, and **Laura Dee**.

We also want to thank our client, Olazul, especially **Beau Perry**, **Kristin Reed**, and **Emmanuel Guevara,** for their continued support throughout the project.

We gratefully acknowledge the **Environ Foundation** for generously providing financial support for this project.

Additionally, we want to recognize the following organizations and individuals whose scientific and technical expertise was invaluable to the development of our project:

CIBNOR - La Paz
Humberto Villarreal
Berenice Hernandez
Laurence Mercier
Violeta Gleaves
Jose Naraujo
Alfredo Hernandez Llamas

CIBNOR - Guaymas
Marco Porchas
Sara Burrola

NOS, Noroeste Sustentable
Alejandro Robles
Cristián Rivera
Lilianna Gutierrez

P. I. A. S. A.
Alejandro Flores-Tom
Alejandro Flores-Marquez

UCSB, Bren School of Environmental Science & Management
Dan Ovando
Ben Best
Lindsey Peavey
Leah Gerber
Bruce Kendall
James Frew

Ocean Farm Technologies
Barry Trexler
Cliff Goudey
Steve Page

University of RI
Barry Costa-Pierce

UCSB Marine Science Institute
Andrew Rassweiler
Libe Washburn

UCSB Department of Geography
David Siegel, PhD

UCSB Marine Map
Chris Macdonald
Will McClintock
Chad Burt
Jared Kibele

Pesquera Delly
Gustavo Valdez

The Nature Conservancy
Anne Gondor

Comunidad y Biodiversidad
Jorge Torre

UCSB Map & Imagery Lab

# Table of Contents

# Abstract

Global demand for shrimp is currently met through fishing and farming practices, both of which are frequently environmentally and economically unsustainable. Offshore aquaculture is an emerging alternative that shows promise for reducing or eliminating many concerns embedded in existing capture fishery and land-based aquaculture practices. Aquapods are a new offshore aquaculture cage system that could provide a path to sustainable shrimp production, but little is known regarding the optimal placement strategy or economic viability of this new technology. This project uses an innovative spatial bio-economic analysis to provide a strategic framework for implementing offshore shrimp aquaculture with greater certainty of success. To better inform the planning, management, and research priorities of Aquapod operations in Northwest Mexico, this project couples marine spatial planning with bio-economic modeling and sensitivity analyses to identify suitable sites for Aquapod implementation and evaluate the economic viability of Aquapod operations. Our model indicates that only a small proportion of our study areas are suitable for Aquapod implementation and that none of the potential locations are expected to be profitable under a “business-as-usual” scenario. We found that profitability is driven by both spatial variability and operational decisions, thus, managers can achieve positive profits and ensure the economic viability of Aquapod operations by locating Aquapods close to shore and reducing feed and labor costs.

## List of Tables

## List of Figures

## List of Appendices

## List of Acronyms

**ArcGIS** – Geographic Information Systems software program developed by ESRI
**CIBNOR** –Center for Biological Research Northwest (Centro de Investigaciones Biológicas del Noroeste)
**COBI** – Comunidad y Bioversidad
**CONAPESCA** – National Commission of Aquaculture and Fisheries (Comisión nacional de acuacultura y pesca)
**CPUE** – Catch per unit effort
**ENPV** – Expected net present value
**ESRI** – Environmental Systems Research Institute
**FCR** – Feed conversion ratio
**GIS** – Geographic Information Systems
**GoC** – Gulf of California
**KML** – Keyhole Markup Language, file type
**M** – “Millions” of US Dollars
**MATLAB** – a technical computing software program (Mathworks, Inc.)
**MSP** – Marine spatial planning
**NGO** – Non-governmental organization
**NOAA** - National Oceanic and Atmospheric Administration
**NOS** – Noroeste Sustentable
**NPV** – Net present value
**OFT** – Ocean Farm Technologies
**SAGARPA** – The Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (Secretaría de Agricultura, Ganaderia, Desarrollo rural, Pesca y Alimentación)
**SCUBA** – Self Contained Underwater Feeding Apparatus
**SEMARNAT** – The Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales)
**SEPESCA** – The Ministry of Fisheries (Secretaría de Pesca)
**SST** – Sea-surface temperature
**TEDs** – Turtle excluder devices
**TNC** – The Nature Conservancy
**USD** – United States Dollar

# Executive Summary

Shrimp is one of the most highly demanded seafood commodities around the world. Approximately six million tons of shrimp are traded annually and shrimp is the highest valued internationally traded fishery commodity (Gillett, 2008). In Mexico, it is the most valuable seafood export, with shrimp industries providing many regional jobs and economic benefits (CONAPESCA, 2007). However, current harvesting practices of bottom trawling and traditional shrimp farming through land-based aquaculture are frequently environmentally and economically unsustainable. Shrimp trawling causes seafloor habitat damage and results in high levels of non-target species bycatch (Dubay et al., 2010). Land-based aquaculture often degrades valuable coastal habitat and results in the discharge of excess nutrients, antibiotics and other pollutants into the environment.

Olazul, our project client, is a non-profit organization that aims to assist coastal communities with their transition from a dependency on destructive seafood farming and trawling practices to more ecologically and financially sound livelihoods. Olazul is interested in exploring offshore shrimp aquaculture as an alternative to trawling and land-based aquaculture, as it shows promise for reducing or eliminating many of the problems embedded in these practices. Offshore aquaculture operations located in deep water off the coast may benefit from ocean currents, which could bring in nutrients and oxygen for the shrimp and flush out wastes. Aquapods are a new offshore aquaculture cage system that could provide a path to sustainable shrimp production, but little is known regarding the optimal placement strategy or economic viability of this new technology. As an emerging use in crowded coastal waters, there are potential user conflicts, as well as uncertainty about how location may affect the economic viability of Aquapod operations. In the absence of proper planning, offshore aquaculture may be implemented in a haphazard or “trial-and-error manner,” which could incur unnecessary environmental and financial costs and increase the likelihood of user conflicts.

**Objectives**

The purpose of this project is to provide Olazul with a set of modeling and planning tools that will provide a strategic framework for implementing offshore shrimp aquaculture with greater certainty of success. Coupling marine spatial planning with bio-economic modeling and sensitivity analyses, this project identifies suitable sites for Aquapod implementation and evaluates economic viability of Aquapod operations. Our innovative spatial bio-economic analysis can be utilized to better inform the planning, development, and future research priorities for Aquapod operations in Northwestern Mexico. There are four specific objectives of this project:

- To develop a site-suitability analysis tool to **identify potential deployment sites** for Aquapods in the Bay of La Paz, Magdalena Bay and Guaymas Bay.
- To develop an adaptive, spatial bio-economic model to **determine how spatial variability, biological growth, and socioeconomic parameters affect profitability** of Aquapod operations in these bays.
- To perform a sensitivity analysis on profitability projections to **inform future research priorities and best management practices** for Olazul.
- To demonstrate how our model can be used to **improve management planning and practices** by evaluating alternative management scenarios.

**Approach**

We chose three diverse study areas in Northwestern Mexico in which to model Aquapod site-suitability and spatial profitability. In order to inform optimal Aquapod siting, best management practices, and future research priorities for successful Aquapod implementation and operation, we designed a comprehensive framework to test site-suitability and economic profitability of shrimp Aquapod aquaculture in these three bays. Our approach can be broken down into a three-step process:

1) A site-suitability analysis for each study area to produce maps of suitable areas for Aquapod siting and an interactive site-suitability tool.
2) A spatial bio-economic analysis to produce maps of spatial profit within the suitable areas for each of the bays.
3) Sensitivity analyses to test the sensitivity of the spatial bio-economic model to various input parameters.

*Step 1. Site-Suitability Analysis*

We identified five spatial parameters that constrain Aquapod siting: (1) depth, (2) benthic slope, (3) marine reserves, (4) shipping lanes, and (5) incompatible existing uses. We used GIS spatial planning tools to develop a site-suitability model and maps of the suitable zones for each study area based on these five spatial constraints.

*Step 2. Spatial Bio-economic Analysis*

Our spatial bio-economic model determined how Aquapod profitability would vary spatially within the suitable area in each bay. Profitability in our model was measured as net present value (NPV), or discounted profits over time. Profits from Aquapod operation are dictated by revenues and costs, which are driven by operational, biological, and spatial factors. Revenues in our model are a function of price and shrimp biomass at harvest, both of which depend on shrimp growth rate. Costs in our model consist of capital startup costs, operational costs, and costs associated with risk. To account for uncertainty in our model parameters, we performed a Monte Carlo simulation over multiple iterations to generate a distribution of NPVs from which we calculated an expected NPV for each suitable location with each bay.

*Step 3.Sensitivity Analyses*
To inform research priorities for Olazul, we performed two different sensitivity analyses on model parameters to determine 1) which parameters the model is most sensitive to, and 2) which parameters cause the most uncertainty in the model output. An elasticity analysis measured the relative response of the model output (NPV) to a percent change in individual parameters. A "parameter value range" sensitivity analysis measured the range in NPV values that result from evaluating the minimum and maximum values for each parameter.

We performed these analyses on two different business models: (1) a small-scale model using small Aquapods, or Micropods, which could support a community-based artisanal farming operation, and (2) a large-scale model using larger A-7000 Aquapods, which that could support an industrial park of Aquapods run by a large business owner or corporation. The focus of our study was the smaller artisanal model, on which we performed all analyses at all sites. The larger industrial model was only evaluated on a more limited scale in La Paz.

**Conclusions**
Our site-suitability analysis found that only a small proportion of La Paz, Guaymas and Magdalena Bays are suitable for Micropod siting: 7 percent, 11 percent and 16 percent, respectively. The resulting maps from our site-suitability analysis illustrated that depth was the most important environmental driver in all three bays in determining the suitable area for Micropod and A-7000 siting.

Our spatial bio-economic model, which is based on current Aquapod pilot operations, found that none of the Micropod sites within the suitable areas are expected to be profitable over a 20 year time horizon, ultimately highlighting inefficiencies in the current pilot management process. However, NPV was not homogenous across each of the suitable areas, indicating that spatially dependent variables, such as fuel costs, temperature and risk proximity, played a large role in the profitability of Aquapod operations. Proximity to launch sites is one of the primary spatial factors influencing profitability, however positioning Micropods adjacent to aquaculture and pollution outflows can negate the benefits of having a launch site close by. Results from our sensitivity analyses were used to inform the alternative management scenarios we explored in our artisanal model. Feed and labor costs were two of the top ranking results in both our elasticity analysis and parameter value range analysis. Reduction of feed and labor costs in the model to mimic management decisions (e.g., installing an automatic feeder, researching alternative feed sources) increased the number of profitable sites to 100 percent. The location of the operation is still an important determinant of profitability due to spatial variability. By reducing feed and labor costs *and* utilizing the spatial bio-economic results map to research suitable locations close to shore, Aquapod operators can maximize their chance of securing positive profits.

Trial and error implementation of a new technology can be economically and environmentally costly, which highlights the value of planning and innovative forecasting. Our project demonstrates how careful planning, modeling, and analysis can improve the potential success of offshore aquaculture operations. Our analysis reduces the cost, time, and conflict that would have resulted from alternative implementation methods such as haphazard or trial and error implementation.

**Recommendations to Olazul**

1. **Collect on-site temperature data to validate the model**
   In situ temperature data at the surface and at depth will aid in determining the validity of the sea surface temperature data utilized in our model and its impacts on shrimp growth and feeding rates.

2. **Investigate environmental impacts of Aquapods**
   a) *Establish water quality baselines*
   b) *Measure oceanographic currents*
   c) *Monitor effluent*

3. **Develop a greater understanding of competing uses and risks**
   We recommend that Olazul work with local stakeholders to use the site-suitability results to gain a better understanding of how potential locations may interact or conflict with existing uses and to determine what other risks may pose a threat to Aquapod operations.

4. **Research the feasibility of suggested alternative management scenarios**
   We modeled seven alternative management scenarios that improved both efficiency and profitability of Micropods. Therefore, we urge Olazul to look into the feasibility of these alternative scenarios for future Micropod management.

5. **Research additional beach access points for Aquapod operation deployment**
   As fuel costs are dependent on distance to launch sites and one of the most important drivers of profitability in our model, finding additional conveniently located launch sites could increase potential profitability.

## Problem Statement

Global demand for shrimp is high and will continue to grow. Currently, approximately six million tons of shrimp are traded annually and shrimp is the highest valued internationally traded fishery commodity (Gillett, 2008). In Mexico, it is the most valuable seafood export, with shrimp industries providing many regional jobs and economic benefits (CONAPESCA, 2007). However, the economic importance of shrimp needs to be reconciled with concerns regarding the environmental impacts of shrimp harvesting practices. Trawling for wild shrimp stocks causes considerable habitat damage and results in extremely high bycatch rates (Dubay et al., 2010). Increases in demand for shrimp have led to overfishing of wild stocks, instability in shrimp profits, and a more dangerous working environment for fishermen. These environmental and socio-economic problems have led to an interest in more predictable methods of shrimp production, such as land-based shrimp aquaculture.

Unfortunately, land-based shrimp aquaculture has its own share of problems. The negative environmental impacts of land-based aquaculture include habitat destruction, high water demand, and pollution of local aquatic environments (Páez-Osuna et al., 2003). Mangrove habitat is frequently targeted and converted to aquaculture sites, thus depriving surrounding regions of the significant ecosystem services provided by mangrove forests. Furthermore, the intense nature of pond shrimp farming has led to increased incidences of disease and the extensive use of antibiotics and other chemicals to control disease outbreaks. High levels of pond effluent containing antibiotics and other waste products impact local water resources, causing eutrophication and a range of other environmental impacts (Páez-Osuna et al., 2003).

Together, shrimp trawling and land-based aquaculture have left the environment extremely degraded, and have also left local fishers and farmers without jobs. Many of these displaced community members have turned to illegal forms of fishing, which can be dangerous, and generate only marginal profits at best. Yet communities in Mexico and other parts of the world still depend on coastal resources for their livelihoods and exports. Consequently, in regions where shrimp has traditionally played a big role in the local environment and economy, there is a huge need for more efficient and sustainable alternatives other than trawling, land-based aquaculture and illegal fishing.

Olazul, our project client, is a non-profit organization that aims to assist coastal communities with their transition from a dependency on destructive seafood farming and capture practices to more ecologically and financially sound livelihoods.

The organization is currently investigating the feasibility of growing shrimp offshore in Aquapod Net Pens. Aquapods are a new containment system for marine aquaculture constructed of individual triangular steel mesh panels fastened together in a spheroid shape. This alternative aquaculture model could provide a path to sustainable shrimp production. Through the use of Aquapods, other new technologies and comprehensive planning, Olazul hopes to develop long-lasting improvements for coastal communities and ecosystems, as well as to act as a model for ocean-friendly seafood development.

## Project Significance

Increasing interest in offshore aquaculture as a solution to food security and environmental issues has led to the development of offshore aquaculture legislation in the United States and around the world. This pending legislation is a major driver for the need to provide a comprehensive framework within which sustainable offshore aquaculture can move forward. Despite the growing interest in developing offshore shrimp aquaculture, there are many unknowns regarding the spatial planning and economic viability of offshore aquaculture operations. As an emerging use in crowded coastal waters, there are potential user conflicts, as well as uncertainty about how location may affect economic viability and long term success. Without proper planning, trial and error implementation of new aquaculture technologies could incur unnecessary environmental and financial costs, as well as increase the likelihood of user conflicts.

Given all the uncertainty and potential conflicts surrounding offshore aquaculture, our main goal is to provide Olazul with a set of modeling and planning tools that will provide a strategic framework for implementing offshore shrimp aquaculture with more certainty of success. Data analysis incorporating the bio-economics and spatial dynamics involved in shrimp Aquapod implementation is needed to understand how to best utilize this technology to benefit local communities and successfully integrate offshore aquaculture operations into the spatial planning of coastal areas. Our approach demonstrates that strategic planning is a valuable tool in reducing uncertainty and user conflicts and can help inform offshore aquaculture development in the rest of Mexico and other regions of the world.

## Project Objectives

The purpose of this thesis work is to develop a comprehensive framework to inform the planning, development and future research priorities for Olazul's Aquapod operations in the Gulf of California. Our framework is composed of a two-pronged approach that couples marine spatial planning with bio-economic analyses to produce site-suitability maps and an economic profitability assessment. There are four specific objectives of this project:

1. To develop a site-suitability analysis tool and resulting maps to assess viable areas for potential Aquapod deployment
2. To develop an adaptive spatial bio-economic model to identify the most profitable sites for Aquapod operations
3. To perform a sensitivity analysis on profitability projections to inform future research priorities and best management practices for Olazul.
4. To demonstrate how our model can be used to improve management planning and practices by evaluating alternative management scenarios.

Our main goal is to provide a set of modeling and planning tools to our client to help them implement a potentially successful technology with a higher success rate. Trial and error implementation of a new technology can be costly environmentally, as well as economically. We seek to reduce both costs with strategic site-suitability and spatial bio-economic analyses.

# Project Background

## Global Shrimp Demand

Shrimp are an extremely popular seafood item both in the U.S. and abroad. As a result, shrimp are the most important internationally traded fishery commodity in terms of value. Shrimp constitute 16 percent of the world's catch with approximately six million tons traded annually at a value of 10 billion USD (Gillett, 2008). Americans alone consume more than half a million tons of shrimp per year, and it is the nation's top fishery import (NOAA, 2009).

To meet this massive demand, many countries around the world supply the global market with shrimp products. Thailand, Vietnam, Indonesia, Mexico, and Ecuador are the top five shrimp producing countries, supplying 70 percent of the volume of shrimp imports in the U.S. (THEFISHSITE, 2008). As demand for shrimp continues to increase, all five of these top suppliers managed to increase their market share in terms of both volume and value between the years 2006 and 2007 (THEFISHSITE, 2008).

While all of these countries have ramped up production as demand for shrimp increases, Mexico has shown the most remarkable growth, with a 15 percent increase in U.S. sales by volume from 2006 to 2007 (THEFISHSITE, 2008). Shrimp are now the most valuable seafood export in Mexico, comprising 44 percent of the value of the entire fishing sector, with a total production value of over 675 million USD in 2007 (CONAPESCA, 2007). This valuable industry provides a number of regional economic benefits and jobs to coastal communities in Mexico, but the race to meet the ever increasing demand for shrimp has led to unsustainable destructive fishing and farming practices. This lucrative industry has developed at a high cost to the environment, and imported shrimp has ultimately earned a poor sustainability rating on multiple seafood consumer guides.

## Shrimp Trawling

Wild shrimp is typically caught by bottom trawling where large nets are dragged across the seafloor. This practice results in severe physical disturbances to the ocean floor, as well as to the animals that live there. In addition to the negative benthic impacts from trawling, the trawling gear itself is highly non-selective, gathering everything in its path and resulting in the incidental catch of non-targeted, or bycatch species. The ratio of bycatch to shrimp in the Gulf of California region is 10:1 (Dubay et al., 2010). These physical and biological impacts of shrimp capture are enormous by typical fishing standards.

Mexican inshore shrimp trawling began in Guaymas in the 1920s, and by the 1940s, shrimp vessels' local grounds were fully exploited, leading to the expansion of shrimp trawling throughout rest of the Gulf of California by the 1950s (Cruz-Torres, 2000). The offshore trawl fleet currently dominates the Pacific and Gulf of California trawling grounds, consisting of 1,674 vessels operating between depths of 9 and 64 meters (Gillett, 2008). Although the Gulf of California and the Gulf of Mexico both serve as shrimp trawling grounds in Mexico, 89 percent of total national shrimp production occurs in the Gulf of California (Dubay et al., 2010).

Shrimp landings in Mexico have tripled since 1960 from 66,000 tons to more than 183,000 tons in 2007 (Gillett, 2008). The increased fishing effort has put tremendous pressure on wild stocks, and catches of Mexican Pacific shrimp appear to have reached their maximum (Gillett, 2008). With an ever increasing demand and declining shrimp stocks, the catch per unit effort (CPUE) has also declined, causing fishermen to spend more time fishing to earn less profit. Fuel costs are also of significant concern to fishermen and are typically higher than catch profits, prompting many governments to subsidize fuel in order to keep the industry alive (Foster and Vincent, 2010). These reduced profits and increased costs have made it difficult for fishermen to meet the increasing demand for shrimp. As a result, many fishermen have sold their boats to the larger fleets, resulting in severe economic losses in coastal communities (Hernandez and Kempton, 2003).

In 2010, the economic pressures on the shrimp industry became apparent when the U.S. State Department initiated a trade embargo against wild-caught Mexican shrimp for violation of an international agreement mandating the use of bycatch reduction devices on all trawlers. In order to reduce the effects of shrimp trawling operations on threatened marine turtle populations, the U.S. requires that shrimp trawlers be equipped with "turtle excluder devices" (TEDs) (NOAA, n.d.). These devices enable turtles, as well as other large marine animals, to escape from trap door compartments located at the bottom of the net (NOAA, n.d.). Unfortunately, TEDs allow a portion of the valuable shrimp catch to escape through the trap door along with the trapped sea turtle. In 2010, many Mexican shrimp trawlers succumbed to the pressure to meet the increasing demand by removing the TEDS in order to increase their CPUE, ultimately prompting the U.S. trade embargo (Dubay et al., 2010). In 2009, Mexico exported almost 40,000 tons of shrimp to the US, resulting in revenues of more than US$ 258 million. (TheFishSite, 2008) With the US embargo on wild-caught shrimp, the Mexican shrimp industry faced the possibility of losing this revenue, as well as hundreds of jobs (SourceMex, 2010).

In short, the Mexican shrimp trawling industry's efforts to meet increasing demand have led to widespread benthic habitat destruction and depletion of wild stocks. Declining stocks have led to instability in shrimp profits, prompting trawlers to quit the industry or find illegal ways of increasing their catch. Illegal trawling efforts (such as nets without TEDs) have in turn resulted in embargos that decrease the market for shrimp exports, causing further economic losses and instability in coastal communities. These economic and environmental concerns surrounding shrimp trawling, coupled with depleted fish stocks and increasing global demand, have led to an interest in more predictable and profitable methods of shrimp production, including land-based aquaculture.

## Land-based Aquaculture

Mexican shrimp aquaculture first developed in the states of Sonora and Sinaloa (Dubay et al., 2010). Support for the shrimp aquaculture industry stemmed from (1) the expectation of future profits from an export commodity and (2) job creation in coastal rural regions (Cruz-Torres, 2000). In 1987, the *Secretaría de Pesca* (Secretariat of Fisheries, SEPESCA) created a National Program for Shrimp Aquaculture (*Programa Nacional de Cultivo de Camarón*) to prescribe guidelines for the development of the industry (Cruz-Torres, 2000).

Shrimp aquaculture production grew at an average rate of 21 percent between 1990 and 2008 and currently accounts for 68 percent of total national shrimp production in Mexico (Dubay et al., 2010). In comparison, wild-caught shrimp production, which increased up until the 1980s, has leveled off to a one percent annual growth rate (Dubay et al., 2010). The race to meet global demand for shrimp and increase

Mexican market share has led to insufficient environmental regulations for the shrimp aquaculture industry, ultimately resulting in many negative environmental impacts.

Land-use changes associated with shrimp farm installation are one of the most notable environmental impacts of shrimp aquaculture production. In particular, the depletion of mangrove wetlands and conversion of salt marshes to make way for aquaculture ponds have contributed to habitat loss, excessive erosion and reduction of biodiversity (Páez-Osuna et al., 2003). Eutrophication of surrounding water resources by nutrient-rich shrimp farm effluent impacts local macrofauna and can lead to harmful algal blooms that ultimately affect shrimp production (Páez-Osuna et al., 2003).

While the impacts of shrimp farming on local land and water resources are significant, feed can be one of the most costly inputs to aquaculture, both environmentally and economically. In order to achieve maximum growth in a limited amount of time, shrimp farmers commonly use protein-heavy diets consisting of fishmeal and other land-based protein (Páez-Osuna et al., 2001). The higher the level of protein, the more nitrogen is found in the effluent, resulting in an increase in eutrophication of water resources surrounding the ponds (Páez-Osuna et al., 2001).

The concentrated nature of the ponds also leads to increased incidences of several types of shrimp diseases caused by bacteria, fungi, and parasites (Páez-Osuna et al., 2001). When shrimp are in stressed conditions—as they often are in ponds—they are more susceptible to disease. In order to protect their investment, pond managers will often combat disease with high doses of antibiotics. These antibiotics are then discharged with the effluent into the local environment (Páez-Osuna et al., 2003). Escaping shrimp may also serve as a vector for disease transmission to already depleted wild stocks.

While the Mexican government and many aquaculture farms are working to reduce these negative environmental impacts through stricter pond placement regulations, mandatory disease-free post-larvae for pond stocking, and even innovative feed design projects, the environmental costs of land-based aquaculture remain high.

## Illegal Fishing

Coastal communities in Mexico and throughout the world depend on coastal resources for their livelihoods and exports. As traditional methods of fishing and farming have become less reliable and more environmentally damaging, people have been forced to turn to the more lucrative, yet dangerous illegal fishing trade.

Illegal fishermen tend to fall into two categories: (1) the smaller subsistence fishermen that use destructive fishing practices such as dynamite fishing in protected areas, or (2) the larger commercial fishermen illegally harvesting and exporting valuable finfish such as dorado and other tuna species (Explorado Mexico, 2010). Both types of illegal fishing operations are dangerous for the fishermen as well as the environment. Two decades ago, ninety percent of the Gulf of California's marine life was viewed to be intact and healthy (Pickell, 2009). Now, many experts claim that only about ten percent of that marine life remains, largely because of non-stop, invasive illegal fishing practices (Pickell, 2009). The need for more sustainable livelihood is clear. One potentially viable alternative is to transition illegal fishermen, and struggling trawlers and farmers, to a more sustainable and reliable offshore aquaculture alternative.

## Offshore Marine Aquaculture

Offshore aquaculture shows great promise for improving both the environmental sustainability and economic profitability of fisheries. In many offshore aquaculture operations, commercially viable species are stocked in cages that are suspended in the water column approximately 20 to 60 feet under the surface of the water, depending on the size and location of the cage (Snapperfarm, 2007). Currently, there are only a few companies worldwide engaged in offshore aquaculture in a submerged cage environment, and the offshore farmed species consist solely of varieties of finfish, including cobia, moi and yellowtail (Snapperfarm, 2007).

Near-shore aquaculture operations are subject to low water flows and currents, but in deeper water offshore, strong currents bring in oxygen and nutrients and remove waste (Piszcz, 2006). These offshore conditions could be optimal for growing commercial species and reducing environmental impacts from effluent (Piszcz, 2006). Oceanic conditions are also more stable at depth than Near-shore: salinity and temperature fluctuations, which can affect the health of the species being produced, are more extreme in shallower water depths (Page, 2005). Despite the promise of offshore aquaculture, however, the industry is still in its infancy due to a lack of infrastructure, the novelty of the technology, and uncertainty regarding profitability and environmental sustainability.

One of the first studies to assess the chemical changes to sediments from offshore aquaculture cages found little change in the sediment chemistry associated with the fish farm waste load; however, the findings may have been influenced by the fact that the fish farm had only been in operation for a short time (Aguado-Gimnez and Garca-Garca, 2004). Another environmental assessment of offshore cage production by Alston et al. (2005) found that there were no significant differences in 1) the concentrations of ammonia, nitrate, and phosphate in the water column; 2) organic matter or nitrogen in the sediments or beneath the cages; or 3) macroinvertebrate abundance between the cage and control sites.

## Why Aquapods?

Multiple designs for offshore aquaculture cages are currently being both researched and used in the field. Cage designs include the Sea Station Cage, the OCAT Cage, the JPS cage and the Aquapod (Figures 1-4).

**Figure 1. OCAT cage**

**Figure 2. Sea Station Cage**

**Figure 3. JPS Cage**

**Figure 4. The Aquapod**

**Photos: Atlantic Marine Aquaculture Center, Durham, NH (UNH, 2007).**

The Aquapod is a spherical fish containment system constructed of individual panels of steel mesh and designed for use in open ocean conditions. The system was developed by the Maine-based company, Ocean Farm Technologies. The spherical shape of the Aquapod provides it with superior stability, safety and profitability relative to other offshore cage designs, as spheres evenly distribute force and contain more volume per surface area than any other shape. These properties maximize both cost efficiency and cage strength (OFT, n.d.).

The innovative modularity of the Aquapod allows for customizable cage sizes (OFT, n.d.). Individual triangular panels are secured together to form net pens that are scalable from 115 cubic meters (8 meter diameter Micropods) up to 11,000 cubic meters (28 m diameter Aquapods) (OFT, n.d.). The smaller cage sizes may be more manageable for artisanal fishermen to operate on their own, as these cages require less maintenance and can be both launched and brought to the surface for harvest without the use of heavy machinery.

The Aquapod is the first offshore cage to utilize steel wire mesh netting, which reduces the need for repair and maintenance, and facilitates cleaning, both of which reduce operational costs (OFT n.d.). The wire mesh also reduces predation and escapement (OFT, n.d.), key concerns in both Near-shore and offshore aquaculture. In offshore aquaculture operations in the Caribbean, shark attacks on SeaStation Cages caused fish escapement and production loss that compromised the economic viability of the operation (Benetti et al., 2006). These advances in the stability, safety, modularity and economic efficiency of the Aquapod fish containment system are some of the reasons Olazul chose Aquapods as the most advantageous cage design for offshore shrimp aquaculture in Mexico.

## Research Needs in Offshore Shrimp Aquaculture

Despite the potential of and growing interest in offshore shrimp aquaculture in Aquapods, there are many unknowns regarding the spatial planning, environmental impacts and economic viability of offshore shrimp aquaculture operations. Preliminary environmental assessments have shown that offshore finfish aquaculture operations produce minimal environmental impacts, but studies to date have been limited in the scope of the research, the species studied and the scale of operation addressed (Aguado-Gimnez and Garca-Garca, 2004; Alston et al., 2005; Benetti et al., 2006; Snapperfarm, 2007). In their analysis of cobia production in Aquapods, Benetti et al. (2007) found that cobia could be biologically viable without "significant environmental impact," however; the researchers do not provide an adequate explanation of how "significant environmental impact" was determined. This assessment is also based on a small-scale operation and does not include recommendations of what the impacts of a large-scale commercial operation may be. Finally, this study does not address the economic feasibility of offshore cobia aquaculture under varying oceanographic and socioeconomic conditions or its applicability to other species.

To the best of our knowledge, there is no existing scientific literature addressing the economic viability, spatial planning or environmental impacts of offshore shrimp aquaculture. Existing data on shrimp operations focus on traditional aquaculture practices in freshwater, terrestrial or coastal ponds. Although studies of land-based shrimp aquaculture and offshore finfish aquaculture provide insight into the potential economic viability and environmental impacts of offshore shrimp aquaculture, they are not directly applicable. The location and environmental conditions unique to offshore shrimp aquaculture dramatically change the economic and environmental dynamics of shrimp aquaculture. As a result, economic and environmental responses in Aquapods will be different than those of traditional aquaculture.

Data analysis incorporating the biological, economic and spatial dynamics involved in shrimp Aquapod implementation is needed to understand how to best utilize this technology to benefit local communities and successfully integrate offshore shrimp aquaculture operations into marine spatial planning of coastal areas. In order to minimize user conflicts and to maximize profitability, it is important to use marine spatial planning tools to identify the locations where offshore shrimp aquaculture in Aquapods is suitable, as well as accessible to and profitable for fishers. Furthermore, if offshore shrimp aquaculture is to be promoted as a sustainable alternative livelihood for Mexican shrimp trawlers or aquaculture farmers, it is essential to use bio-economic modeling to determine whether shrimp production in Aquapods is economically viable, and how profitability depends on spatial variability.

## Marine Spatial Planning

Marine spatial planning (MSP) is a management tool that can be used to balance the impacts and conflicts generated by multiple, overlapping marine resource uses with marine ecosystem conservation. Through spatial zoning of the ocean for specific uses, MSP can provide significant economic, social and ecological benefits by reducing user conflicts, increasing resource use efficiency, improving safety, and increasing biodiversity conservation (Elher and Douvere, 2009). Another benefit of this approach is increasing the coordination between various authorities to meet their objectives through a broader planning process. This coordination helps to alleviate existing coastal management problems that stem from overlapping agency jurisdictions and mandates (Ray, 2010).

Geographic Information Systems (GIS) have been used increasingly to site emerging uses, including offshore energy development and open ocean aquaculture, in marine spatial plans. Benetti et al. (2006) assert that site selection is the most crucial step in ensuring environmental sustainability and successful implementation of offshore aquaculture operations for cobia and snapper. Their site selection was based on parameters related to infrastructure, topography, bathymetry, meteorology, hydrology, environmental and biological information, as well as the legal, social, economic and political framework of the Caribbean (Benetti et al., 2006). This prior study highlights site selection and spatial planning as an important priority for offshore aquaculture development, but the authors do not provide a model for site selection applicable to other species or locations, nor do they elaborate on their selection criteria. A site-suitability planning framework incorporating the environmental, economic and spatial dynamics involved in shrimp Aquapod siting is needed to understand how to best utilize GIS to benefit local communities and successfully integrate offshore shrimp aquaculture operations into marine spatial planning of coastal areas with many ongoing activities.

## Bio-economic Analysis

Both economic modeling and biological modeling have been used extensively in their respective fields to construct representations of real-world situations. However, the use of bio-economic models is a relatively recent marriage between the two that incorporates biological functions into the economic model. Bio-economic models are generally used when an economic output is dependent upon biology in some fundamental way (Kazmierczak, 1995). For instance, a farmer's production of corn depends upon the biological growth and mortality rates of his crop, which both vary as a function of weather and climate.

Bio-economic models vary depending on their specific goals. They are capable of integrating existing data and concepts, identifying gaps in research, screening potential experiments, hypothesis testing, and determining best operating conditions and management practices for a given production system (Cacho, 1997). The purpose of a bio-economic model is to mimic a real system with enough accuracy to obtain valuable information without having to invest resources into long-term field and/or research studies.

Bio-economic models have been used to model production operations ranging from asparagus harvesting in Washington state (Cembali et al., 2004) to offshore aquaculture production of Pacific Threadfin in Hawaii (Kam et al., 2002). Bio-economic models of offshore aquaculture incorporate environmental forces that typical pond aquaculture models avoid and, thus, tend to be more complex. Our project is an excellent candidate for bio-economic modeling, given the high capital costs associated with field experiments and the lack of knowledge associated with offshore shrimp aquaculture. Developing a bio-economic model for shrimp Aquapod production allows us to determine the best operating conditions, assess the relative importance of our input parameters, evaluate various management practices for economic success, and conduct preliminary testing of hypotheses related to Aquapod success.

## Spatial Bio-Economic Analysis

In considering the marine spatial planning and bio-economic components of Aquapod implementation, we recognized that some biological and socio-economic parameters vary spatially. For example, shrimp growth is dependent on water temperature, which varies spatially. Consequently, a site in warmer water might have higher growth rates than a site in cooler water, ultimately yielding a greater shrimp biomass leading to higher profits. We therefore decided to incorporate this spatial variability into our bio-economic analysis by developing an innovative spatial bio-economic model. This model incorporates the conventional biological and economic parameters that impact profitability, but also uses spatial data to determine how Aquapod siting would affect profitability of Aquapod operations. To the best of our knowledge, there is no existing scientific literature addressing similar spatial bio-economic models, therefore we developed our model using input from experts in the economic and spatial modeling fields.

# Methodology

## Background on Study Areas

In consultation with our client and stakeholders, we chose three diverse study areas in Northwestern Mexico in which to model Aquapod site-suitability and spatial profitability: Guaymas Bay, Magdalena Bay, and La Paz Bay (see Figure 5). The locations were chosen to explore whether a single modeling framework could be successfully applied to a diverse array of locations. Each site has different spatial, environmental and economic conditions, which have the potential to impact Aquapod implementation.


**Figure 5. Map depicting the three study areas within which we modeled site-suitability and spatial profitability of Aquapods: Guaymas (top), La Paz (bottom right), Magdalena Bay (bottom left).**

## Guaymas Bay

Guaymas has a population of 134,153 and is located in the state of Sonora on the mainland side of the Gulf of California (INAFED, 2010). It is home to a once-thriving, but now suffering fishing community with over 80 percent of the population employed by the fishing industry (INAFED, 2010). Destructive fishing practices, such as trawling, together with illegal fishing activities have devastated local fishing communities in Guaymas (Mahdi and Robertson, 2010). Trawling vessels catch a majority of shrimp in the region, and overfishing and the habitat destruction caused by trawling gear have decreased shrimp biomass in the region. Decreased biomass has translated into decreased catches and fishing profits (Mahdi and Robertson, 2010). These conditions have made it difficult for local communities to sustain themselves, thus they are turning to other industries to support their livelihoods (Mahdi and Robertson, 2010). Processing (e.g., canning and freezing) of fish products is also a main industry of the town (INAFED, 2010). Although land-based shrimp aquaculture first began in the area as early as the late 1970s, Guaymas remains mostly a commercial fishing port (INAFED, 2010). In addition to its commercial fishing industry, Guaymas' close proximity to the United States has attracted tourists year round, creating a thriving sport fishing industry (INAFED, 2010).

Most industrial activity takes place in the main port of Guaymas on the northern side of the bay, while tourism activities take place in the nearby port of San Carlos (INAFED, 2010). Sandy beaches and mangroves line the southern section of the bay with less than 30 percent of the population living in these areas (INEGI, 2005). Those that do live in the rural areas tend to be fishermen. Both the rural communities and the commercial fishermen would benefit from the increased stability of revenue that Aquapod shrimp aquaculture offers. The depressed commercial trawling economy has already inspired the local fishing company Pesquera Delly to look for alternatives and, in 2009, they started the first pilot trial of shrimp Aquapods.

With the majority of the Guaymas population accustomed to making their living from ocean resources, Guaymas would appear to be an ideal candidate for transitioning struggling fishermen to more sustainable livelihoods through shrimp Aquapod implementation. Three major hurdles may inhibit Aquapod implementation in this study area: (1) The industrial nature of the port. Large ships from the petroleum and commercial shipping industries frequently traverse the bay and multiple industrial sites release toxic effluent into the bay. Both of these factors may reduce the suitability of the site; (2) Risk of disease. Due to existing land-based shrimp aquaculture in the area, there may be a higher risk of disease transfer to Aquapods; (3) Lack of community interest. Little outreach work has been done within the communities to promote sustainable alternatives and few stakeholders are aware of and interested in this new technology.

## Magdalena Bay

Magdalena Bay is located on the Pacific side of the Baja peninsula at the meeting point of the cooler California Current system from the north and the warmer Equatorial Countercurrent from the south (Smith, 2004). This confluence creates unique oceanographic conditions, including large areas of upwelling of nutrients, which result in high productivity levels within the bay (Smith, 2004). Two barrier islands, Isla Magdalena and Isla Santa Margarita, protect the bay from the harsh conditions of the Pacific Ocean and as a result, biodiverse estuaries line the edges of the bay (Smith, 2004). The protected nature of the bay also makes it a favorite nursery spot for the migrating gray whale. Each year 250-500 whales migrate to the bay to birth their young (Learner, n.d.).

The 3,200 residents of Magdalena Bay have relatively few choices for employment (Smith, 2004). The only year-round industry is a sardine processing plant, which employs over 500 people (Smith, 2004). Other sources of income stem from whale-watching tour services and shrimp trawling. Eco-tourism—including kayaking, whale watching and sport fishing—is becoming more popular, but the revenue derived from this industry is seasonal and the market is flooded with tour operators (Smith, 2004). Revenue from commercial fishing is also low. As Bain Smith from Seawatch described after a night of shrimp trawling, "The boat has killed 300 lbs of juvenile fish to get 30 lbs of shrimp that are sold for $140.00. It has used 135-150 liters of fuel, 7 liters of oil, costing about $105.00. The income for the night's work for two people is approximately $35.00" (Smith, 2004).

Magdalena Bay's protected, nutrient-rich water would be an ideal place for Aquapod shrimp production. Communities that struggle to maintain an income year-round would potentially be able to secure long-term increased revenues from Aquapods while reducing damage to the environment. There are two main concerns, however, that would need to be addressed before Aquapod aquaculture could be implemented in Magdalena Bay: (1) How will the gray whales interact with the pods and will the pods impact the nursery grounds? and (2) Is there a sufficient workforce present in Magdalena Bay to be able to operate and maintain the pods?

## Bay of La Paz

La Paz is located on the Gulf side of the Baja peninsula and is the capital city of the state of Baja California Sur. The actual city has a population of 189,176, but the entire metropolitan population is approximately 200,000 persons (INEGI, 2005). La Paz has one of the highest standards of living and quality of life in Mexico, with average wages in the range of 27 USD per day, whereas minimum wages in the country overall stand at closer to 4.25 USD per day (Stanford, 2010). The higher average wage in La Paz is a result of the healthy tourism industry in the area. Eco-tourism is by far the major source of tourism income in La Paz, as people come to enjoy a variety of marine activities from diving and fishing to sailing and kayaking (Stanford, 2010). La Paz is also home to one of Mexico's largest research institutes: the Center for Biological Research Northwest (CIBNOR). Their mission is to contribute to the welfare of society by conducting scientific research, technological innovation and human resources training in the management of sustainable natural resources (CIBNOR, n.d.). CIBNOR is currently researching and developing alternative aquaculture practices and is interested in Aquapod technology as one method of increasing Mexico's aquaculture exports (H. Villarreal, personal communication, June 8, 2010).

On the outskirts of the city, the relatively developed nature of La Paz diminishes. Many communities struggle to make a living from local coastal resources. Fishing camps outside the city have turned towards illegal night fishing in protected areas to in order to maintain a living (C. Rivera, personal communication, June 8, 2010). During a site visit to La Paz, we learned that Noroeste Sostentable (NOS), a non-governmental organization (NGO) in La Paz, works with these fishing communities to educate them on the value of protecting marine resources and has developed programs to transition illegal fishermen to the more lucrative tourism industry. NOS is interested in the development of Aquapod shrimp aquaculture as a potential alternative livelihood for the illegal fishermen with whom they currently work.

La Paz has a unique blend of quality marine resources and a public with a vested interest in protecting these resources, which creates optimal conditions for more sustainable offshore aquaculture development. Partnerships with local agencies such as CIBNOR and NOS also improve the chances for the success of Aquapod development in the bay. The only potential drawback to La Paz is that some of the more southern parts of the bay are more exposed to the ocean conditions of the Gulf of California, resulting in potential risks during the hurricane season.

## General Approach

In order to inform Aquapod siting and make recommendations to Olazul on future research priorities and best management practices for successful Aquapod implementation and operation, we designed an Aquapod evaluation framework to test site-suitability and economic profitability of shrimp Aquapod aquaculture in three coastal communities. This framework can be broken down into a three-step process:

1) A site-suitability analysis for each study area to produce maps of viable areas for Aquapod siting and an interactive site-suitability tool.
2) A spatial bio-economic analysis to produce maps of spatial profit within the viable areas for each of the sites.
3) Sensitivity analyses to test the sensitivity of the spatial bio-economic model to various input parameters.

The overall approach to the project methodology is shown in Figure 6. First we used GIS spatial planning tools to perform a site-suitability analysis for each of our three study areas and used the results to develop a site-suitability GIS tool. The resulting areas that are suitable for Aquapod placement were then used to define the spatial boundaries within which we calculated spatial profit. We used both spatial layers (extracted from GIS) and non-spatial parameters to inform the spatial bio-economic model for calculating spatial profit,). We then mapped the output of this profit model in GIS. We also completed sensitivity analyses on parameters of the spatial bio-economic model.

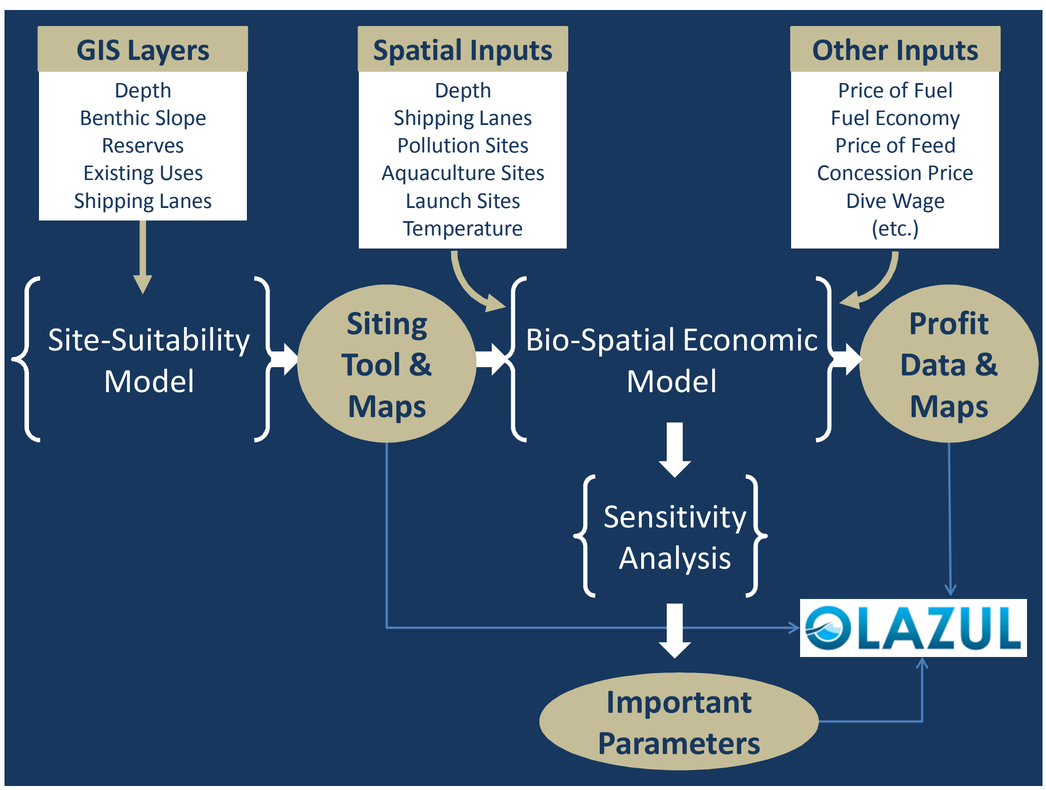



**Figure 6. Overview flow chart of project methodology including raw data inputs (boxes), models and calculations (brackets), and deliverables to Olazul (tan circles).**

We performed site-suitability and spatial bio-economic analyses on two different business models: (1) a smaller model that could support a community-based artisanal fishery, and (2) a larger model that could support an industrial park of Aquapods run by a larger entity. We decided to evaluate the artisanal model to support Olazul's goal of exploring Aquapods as a viable strategy for transitioning artisanal communities to more sustainable livelihoods, while we evaluated the industrial model to explore the potential for transitioning large trawling companies to more sustainable offshore opportunities. The focus of our study was the smaller artisanal model, which we evaluated at all three study sites. The larger industrial model, however, was considered as an alternative and was evaluated on a more limited scale in La Paz only.

In the artisanal business model, the operators use a panga (a small, shallow-draft boat), a larger maintenance boat and SCUBA divers to service an array of nine Micropods. These Micropods are eight meters in diameter and, as shown in the schematic in Figure 7, each individual Micropod is affixed to a central single-point mooring. The mooring and pod together occupy a space with a radius of 50m from the central mooring point. With this in mind, the cell size of our analysis (300m x 300m) is dictated by the smallest area that could accommodate a square grid of nine pods spaced at the minimum distance compatible with these single-point mooring constraints. The business model is based on farming of native brown shrimp, with two five-month (or 20 week) growing seasons per year during the months of the year that exhibit the warmest water temperatures in each bay.

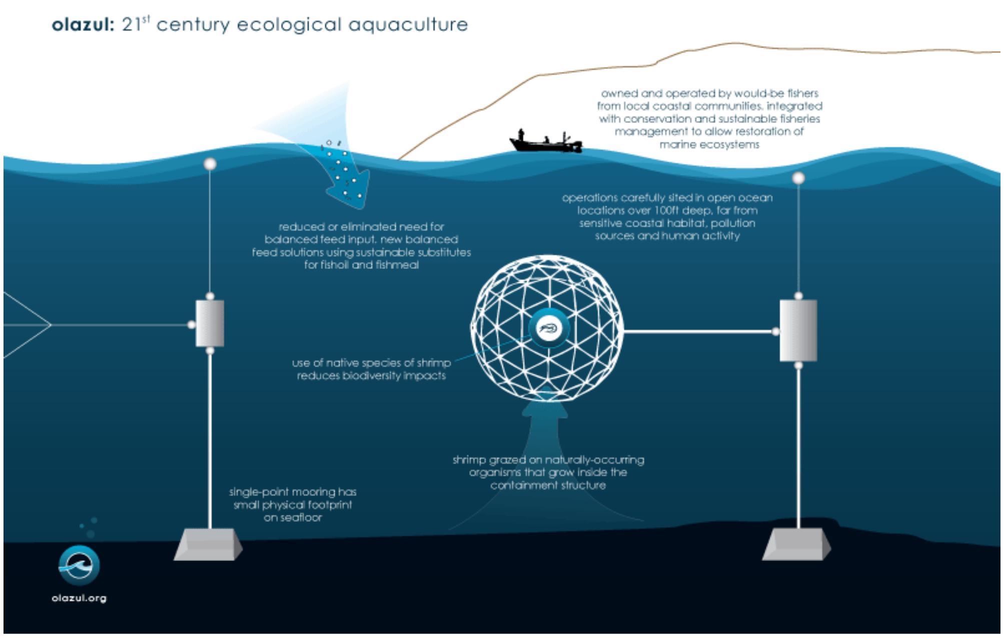



**Figure 7. Schematic of Aquapod single-point mooring.**

In the industrial park business model, the operators use a trawler, a platform boat, a panga, divers and a Remote Operated Vehicle (ROV) to service an array of 16 A-7000 Aquapods. These larger A-7000s are 24 meters in diameter and, as with the Micropods, each individual A-7000 is affixed to a central single-point mooring. The mooring and pod together occupy a space with a radius of 70 meters from the central mooring point. The cell size of our analysis (700m x 700m) is dictated by the smallest area that could accommodate a hollow square of 16 pods spaced at the minimum distance compatible with these single-point mooring constraints. In contrast to the Micropod grid layout, the A-7000s are arranged in a “hollow” square pattern to allow larger industrial vessels to maneuver safely around the pods. As with the Micropods, the industrial business model is based on the farming of native brown shrimp, with two five-month (or 20 week) growing seasons per year, during the months of the year that exhibit the warmest water temperatures in each bay.

In the following analysis, we use the term “Aquapod” when referring to the net pen containment system in general, the term “A-7000” to refer specifically to the large pods, and the term “Micropod” to refer specifically to the smaller pods.

## Step 1. Site-Suitability Analysis

Based on consultation with our client and other experts, we identified five spatial parameters that constrain Aquapod siting: (1) depth, (2) benthic slope, (3) marine reserves, (4) shipping lanes, and (5) incompatible existing uses. We used GIS spatial planning tools to develop a site-suitability model that generates maps of the suitable zones for each study area based on these five spatial constraints.

### Data

To begin our analysis, several partners provided us with spatial data, and we generated additional spatial data using Google Earth. The sources and format for each data layer at each study area are summarized in Table 1.

The shapefile and feature class data layers were all received in GIS-compatible formats. The bathymetric nautical charts for Guaymas, however, needed to be scanned and geo-referenced. We then used the geo-referenced maps to input bathymetric points by hand to create a GIS-compatible, bathymetric point shapefile for Guaymas.

While we received shapefiles of the marine reserves in La Paz, we needed to create the marine reserve data layer for Magdalena Bay (there are no marine reserves in Guaymas). We used Google Earth to generate the one reserve in Magdalena Bay, as defined by boundaries outlined on COBI's website[1]. The Google Earth Marine Reserve KML file was then converted into a shapefile for use in GIS.

**Table 1. Source and format (in parentheses) for site-suitability spatial data for each study area; CIBNOR is the Centro de Investigaciones Biológicas del Noroeste; TNC/COBI is a partnership between The Nature Conservancy and Comunidad Y Biodiversidad.**

| Data Layer[2] | La Paz | Guaymas | Magdalena Bay |
|---|---|---|---|
| Bathymetry | CIBNOR (points shapefile) | Olazul (nautical charts, hard copy) | CIBNOR (points shapefile) |
| Marine Reserves | CIBNOR (polygon shapefile) | NA | Google Earth (KML file) |
| Shipping Routes | TNC/COBI (polyline feature class) | TNC/COBI (polyline feature class) | NA |
| Existing Aquaculture | CIBNOR (polygon shapefile) & Google Earth (KML file) | Google Earth (KML file) | Google Earth (KML file) |

While we received some existing aquaculture data for the La Paz study area, we generated additional aquaculture data for La Paz, as well as for the other two study areas, using Google Earth. To identify the sites of these competing uses, existing aquaculture was defined as offshore aquaculture pens that were visible in Google Earth (we defined aquaculture differently for the spatial bio-economic model due to organism-specific disease risks; see Risk Costs section). We also included the location of the array of offshore Aquapods currently installed in the pilot trial in Guaymas in the existing Aquaculture data layer. The Google Earth KML files for existing aquaculture were then converted into shapefiles for use in GIS.

[1] COBI website showing Magdalena Bay marine reserve: http://www.cobi.org.mx/?pag=r-pbc-isla-magdalena&idioma=esp

[2] Regardless of origin or file type, all data layers were projected into the UTM NAD 1983 Zone 13 projection.

## Developing the Site-Suitability Model

Before developing a site-suitability model, we first had to define the five constraints for Aquapod siting: (1) depth, (2) benthic slope, (3) marine reserves, (4) shipping lanes, and (5) incompatible existing uses. The first two parameters, depth and benthic slope, are driven by technical and mooring constraints. Micropods can be moored only in depths greater than 15 meters (due to the diameter of the pod) and less than 45 meters (due to the limits of safe diving depths) (C. Goudey, personal communication, July 7, 2010). A-7000s can be moored only in depths greater than 48 (again, due to the diameter of the pod) and less than 150 meters (dictated by and commercial diving constraints) (EPRI, 2006). Both sizes of Aquapods can be moored only on slopes with grades of ten percent or less (B. Trexler[3], personal communication, July 16, 2010). In order to incorporate depth into our siting model, we used GIS tools to interpolate the bathymetric point data we received into a continuous bathymetric field for each of our study areas. From this bathymetric depth field, we then used GIS to calculate benthic slope.

The other three spatial parameters (shipping lanes, incompatible existing uses, and marine reserves) can be generally categorized as areas from which Aquapods must be excluded. The marine reserve data clearly delineated areas of marine reserves. Unlike marine reserves, however, the shipping data we received consisted of polyline navigation *routes* only (i.e., the routes had no width, as would a regulated shipping lane). Consequently, we had to define the width of the shipping lane from which Aquapods would be excluded. Uni-directional shipping lanes in the U.S. generally have a width of one nautical mile (S. Green, personal communication, December 7, 2010). We therefore used this same width to define the shipping "lanes" in our study areas. Based on available data, the only identifiable incompatible existing uses in our study areas were offshore aquaculture operations. It should be noted however, that if additional areas of incompatible use were identified, they could easily be incorporated into the existing use spatial layer, for use in the site-suitability model.

Once we had identified, defined and mapped these five spatial parameters that constrain Aquapod siting, we used GIS spatial planning tools to develop a site-suitability model in ArcGIS ModelBuilder. The general form of the site-suitability model is shown in Figure 8 on page 26.

[3] Barry Trexler is an engineer with Ocean Farm Technologies.

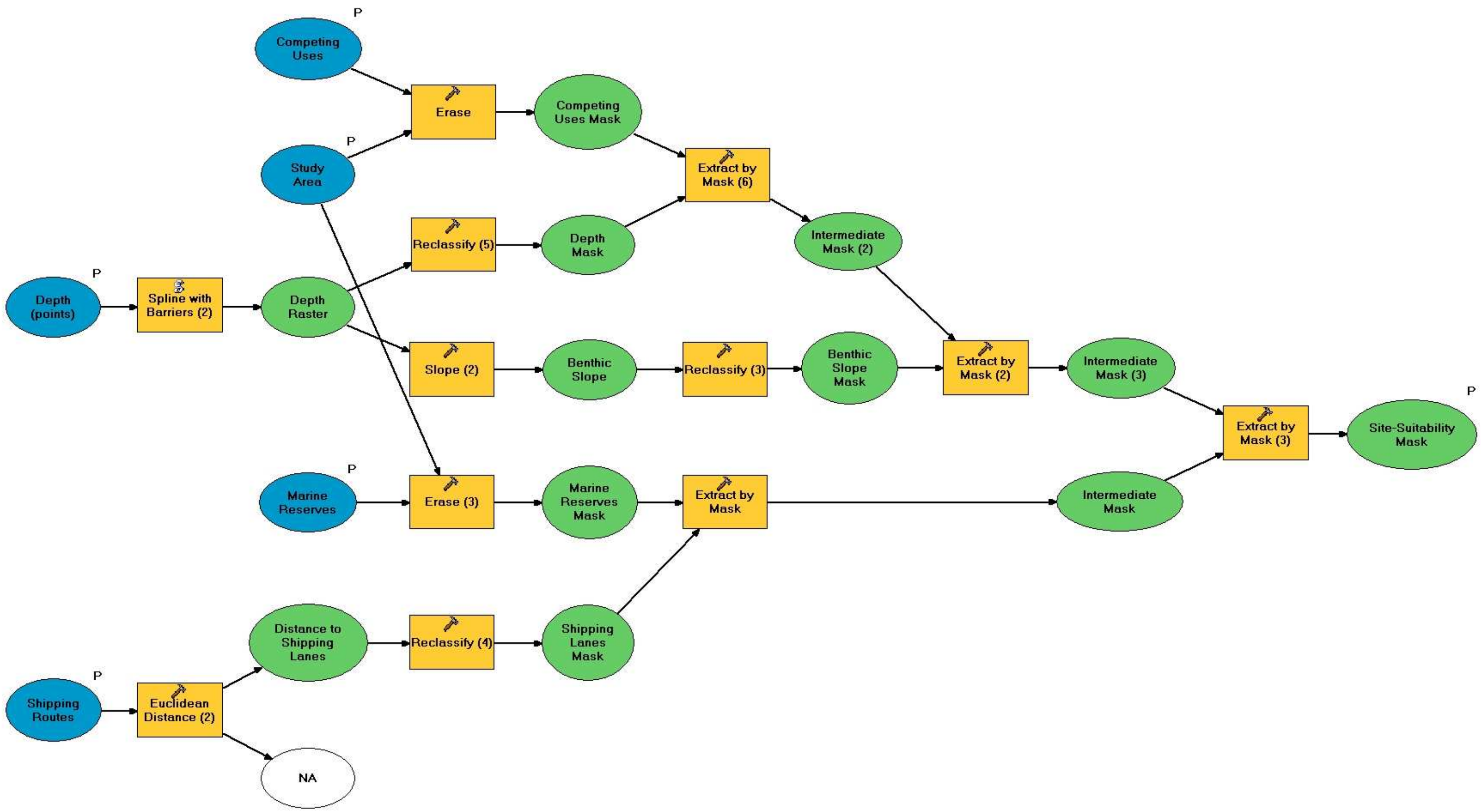



**Figure 8. ArcGIS (9.3) Site-Suitability Model including raw data spatial inputs (blue ovals), ArcGIS modelbuilder tools (yellow rectangles) and generated spatial layer outputs (green ovals).**

The details for each parameter of this model are outlined in the following bullet points:

- Depth: we interpolated the bathymetric points using the "Spline with Barriers" tool to generate a continuous field of bathymetric depth. We then reclassified this field as either suitable (with a value of "1" for suitable depths) or unsuitable (with a value of "no data" for all other depths).
- Benthic Slope: We converted the bathymetric field to benthic slope using the "Slope" tool. We then reclassified benthic slope as either suitable (with a value of "1" for grades of less than ten percent) or unsuitable (with a value of "no data" for grades greater than ten percent).
- Marine Reserves: We cut the marine reserve polygons out of a polygon of our study area using the "Erase" tool.
- Shipping Lanes: We calculated distance to the shipping routes using the "Euclidian Distance" tool. To define our one nautical mile wide shipping "lane," we then reclassified distance to shipping route as either suitable (with a value of "1" where distance to shipping lanes was greater than 926 meters, or half a nautical mile) or unsuitable (with a value of "no data" where distance to shipping lanes was less than or equal 926 meters).
- Incompatible existing uses: We cut the incompatible existing uses out of a polygon of our study area using the "Erase" tool.

We then combined all these layers using the "Extract by Mask" tool to generate a mask of viable areas for Aquapod placement (viability mask) for each study area.

Although the basic version of the site-suitability model is explained here, the actual version varies depending on the applicable parameters at each site. For example, while depth and benthic slope were applied at all three sites, the La Paz study area included shipping lanes and areas of incompatible uses, while the Magdalena Bay study area did not have any applicable shipping lanes or areas of incompatible use.

Another important aspect of this step is that the site-suitability model is designed to be used as an interactive GIS tool. To create this tool, we parameterized the model and saved it as an uploadable GIS toolbox. Parameters marked with a P in the model (Figure 8) can be input by a user before running the model to produce a new output viability mask. Consequently, if new data become available, or if Olazul wants to expand the scope of the project to additional sites, this GIS tool can be used to output a new viability map.

## Step 2. Spatial Bio-economic Analysis

After identifying the suitable sites within the three bays, we next determined how Aquapod profitability would vary spatially within the suitable area in each bay. Profits from Aquapod operations are dictated by revenues and costs, both of which are described in detail in the sections below. A conceptual model of our spatial bio-economic profit model is provided below (Figure 9). This diagram depicts the inputs and outputs of our bio-economic model, which integrates shrimp biology and growth into an Aquapod production system. Both biological and operational components are influenced by spatial factors, including temperature, depth, and distance to launch sites, pollution, aquaculture and shipping lanes.

This conceptual model illustrates the biological, economic, and spatial interactions implicit in Aquapod production. For example, temperature is the primary driver of both shrimp growth and feed consumption rates. The amount of feed consumed emerges as a variable cost in the model, whereas shrimp growth dictates the size of the shrimp at harvest, influencing revenue. The mechanisms and relationships that drive the interactions between all of these parameters are described in detail in the following sections. The equations we derived for our model were developed and processed using MATLAB software.

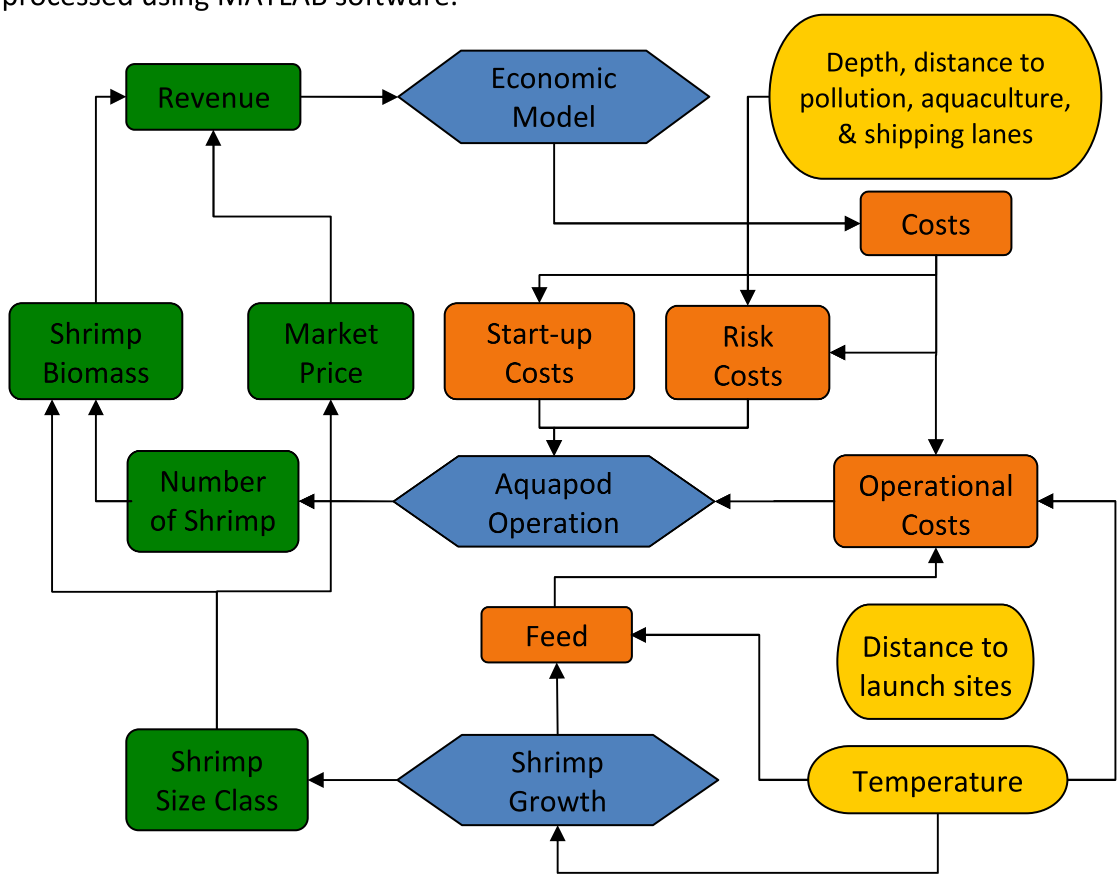



**Figure 9. Conceptual diagram of our spatial bio-economic model, including cost inputs in orange, revenue outputs in green, and spatially-dependent parameters in yellow.**

Our spatial bio-economic model was developed to measure profitability of an artisanal Micropod operation, though we later modified it to evaluate the industrial model (see Industrial Methodology section below). More precisely, we calculated discounted profits over time, or net present value (NPV). To calculate the NPV of each potential Aquapod location, our model discounted yearly profits over a 20 year time period at a rate of five percent annually. Summing each year's discounted profit over our 20 year time frame generated the NPV at every location. To account for uncertainty in model parameters, we performed a Monte Carlo analysis, which ran multiple simulations covering the full range of our defined parameter value ranges. Parameter ranges were determined based on expert consultation, field research, and literature review. Running multiple simulations in MATLAB allowed us to generate a range of NPVs. We then took the average of this range to calculate the expected NPV (ENPV) of an Aquapod operation at each potential deployment site.

## Revenue

Revenue generated from an Aquapod operation is a function of the shrimp biomass in kilograms at the time of harvest ($Biomass_H$) and the price of shrimp at harvest ($P_H$):

$$Revenue = Biomass_H * P_H$$

Revenue Data

Several partners provided us with input revenue data for the bio-spatial-economic model. The source and value for the input parameters for calculating shrimp biomass are included in Table 2.

**Table 2: Revenue parameters and sources.**

| Revenue Parameter | Source |
|---|---|
| Temperature | TNC/COBI |
| Ex-Vessel Shrimp Prices | CleanFish |
| Stocking Density | Pesquera Delly |

Sea-surface temperature (SST) data were derived from National Ocean and Atmospheric Administration (NOAA) climataological time series data covering the period from 1985-2001. The spatial dataset contained monthly average temperatures over this 25 year period, for each of our three study areas. We used the ten warmest consecutive months of temperature data to define our harvest cycle in each bay. Because the SST spatial rasters were of a larger resolution than our cell size of analysis, we sub-sampled the larger cells to generate temperature values for our smaller cell size of analysis. One assumption inherent in this step is that SST is comparable to the temperatures at the depths where Aquapods will be situated. According to expert opinion (B. Costa-Pierce[4], personal communication, June 10, 2010), this assumption is reasonable for a first-cut analysis, as the temperature gradient between the surface and the relevant depths is thought to be negligible due to the intense surface mixing in the region. Given the important role that temperature plays in Aquapod profitability, however, future analyses need to examine this assumption further.

Because we were only interested in calculating profit within the suitable areas for Aquapod placement, each spatial input parameter had to be clipped to the suitable area before being exported. We therefore clipped the twelve monthly temperature rasters to the suitable area for each study site using the "Extract by Mask" tool and the viability mask we had generated from the site-suitability model. We then exported the spatial SST data and its geographic coordinates to an Excel table for use in the bio-spatial-economic analysis (see Appendix D for an excerpt of this table).

Ex-vessel shrimp prices data were developed in consultation with CleanFish[5], a US-based seafood distribution company, which specializes in sustainable products, and Ocean Garden, a large southern California based seafood distributor. Ex-vessel prices were used in our analysis to more accurately reflect the returns that go back to the shrimp producers, as opposed to market prices, which include a markup that the distributor collects. To minimize processing expenses, we assumed a head-on final product, and minimal distribution fees. We assumed Aquapod-raised shrimp would be price-competitive with wild-caught shrimp in Mexico, as Aquapod shrimp may command a higher price than traditionally farmed shrimp due to better taste and higher quality.

CleanFish provided pricing tables for headless, wild-caught Mexican brown shrimp. Prices depended on the size of the shrimp at the time of harvest, as people are willing to pay more for larger shrimp. To determine the price for head-on shrimp, we reduced CleanFish's headless prices in each price category by 30 percent, as recommended by Ocean Garden. In our analysis, we also included a "revenue bonus" of up to 10 percent to account for potential eco-labeling benefits rewarding the possible reduced environmental impacts of Aquapod shrimp farming. For modeling purposes, we assumed uniform distribution of shrimp size during each

---

[4] Barry Costa-Pierce is a Professor of Fisheries and Aquaculture at The University of Rhode Island with expertise in ecological aquaculture. He also serves as a science advisor to Olazul.

[5] CleanFish currently distributes shrimp from Pesquera Delly, the first pilot Aquapod operation in Guaymas.

harvest. Table 3 describes the shrimp pricing size classes and ex-vessel prices utilized in our model.

An estimate for stocking density (400 post-larvae/ $m^3$) was developed from observing Pesquera Delly's Aquapod operations during the summer of 2010. Typical stocking densities from traditional aquaculture literature were not utilized in our model, as they are reported in units of square meters, whereas stocking densities in Aquapods must be in cubic meters.

**Table 3. Shrimp size classes and respective pricing for head-on brown shrimp**

| Shrimp Size | Ex-Vessel Shrimp Price(USD $/kg) | Min Price (USD $/kg) | Max Price (USD $/kg) |
|---|---|---|---|
| Size class A: 10+ shrimp/pound | $16.10 | $16.05 | $16.21 |
| Size class B: 10-12 shrimp/pound | $14.18 | $14.12 | $14.27 |
| Size class C: 12-15 shrimp/pound | $13.72 | $13.66 | $13.81 |
| Size class D: 16-20 shrimp/pound | $11.38 | $11.34 | $11.49 |
| Size class E: 21-25 shrimp/pound | $9.45 | $9.42 | $9.57 |
| Size class F: 26-30 shrimp/pound | $8.75 | $8.65 | $8.80 |
| Size class G: 31-35 shrimp/pound | $7.07 | $7.02 | $7.18 |
| Size class H: 36-40 shrimp/pound | $5.78 | $5.64 | $5.79 |
| Size class I: 41-50 shrimp/pound | $5.43 | $5.40 | $5.56 |
| Size class J: 51-60 shrimp/pound | $5.08 | $4.94 | $5.10 |
| Size class K: 61-70 shrimp/pound | $4.55 | $4.47 | $4.63 |
| Size class L: 71-80 shrimp/pound | $3.68 | $3.63 | $3.78 |

Shrimp Biomass Model

Shrimp biomass at the end of harvest was calculated using the Hernandez-Llamas stock model (Hernandez-Llama et al., 2004) and is determined by the size of the shrimp at harvest ($Finalweight_H$) and the number of shrimp at harvest ($N_H$):

$$Biomass_H = N_H * Finalweight_H$$

To determine the number of shrimp surviving until harvest ($N_H$), we used a population density function adapted from Hernandez-Llamas, et al. (2004) with a fixed, density-independent mortality constant (z). We used this equation to calculate shrimp mortality on a weekly (w) basis, ultimately generating the number of surviving shrimp at harvest (w=20), which was incorporated into the Biomass function.

$$N_w = N_o e^{-zw}$$

*where $N_o$ is initial stocking density, $N_w$ is the number of shrimp at a given week w and z is the density-independent mortality constant*

Calculating the weight of the shrimp at harvest was the other component of our shrimp biomass equation. To determine the average weight of shrimp at harvest, ($Finalweight_w$), weekly shrimp growth and initial post-larvae weight were summed to yield the final average weight of an Aquapod shrimp at harvest:

$$Finalweight_H = \sum_0^w Growth_w + Weight_{initial}$$

Shrimp Growth Model

Because the Aquapod is a relatively new and untested cage technology for offshore aquaculture, there are minimal data available on shrimp growth within an Aquapod production system. To overcome this obstacle, we developed a shrimp growth model to simulate shrimp productivity within an Aquapod.

To determine shrimp growth rates within an Aquapod system, we developed a temperature-dependent shrimp growth model based on Pacific white shrimp (*Litopenaeus vannamei*) growth data from a study conducted by Wyban et al. (1995). Wyban et al. had examined the effects of temperature on the growth and feeding rates of various sizes of white shrimp that fell into three categories: small (0 – 10.8 grams), medium (10.8 – 16 grams) and large (16+ grams).

We graphed the temperature and growth data for each size class and derived the following growth equations by fitting each dataset with the best fit curve, a fourth order polynomial:

$$Growth_{small} = -0.000104548229548085\,T^4 + 0.00678128815628209\,T^3 - 0.139069749694711\,T^2 + 1.20503067765702\,T - 4.87885989012892$$

$$Growth_{med} = -0.000192498473748609\,T^4 + 0.0163161248473876\,T^3 - 0.501469971001686\,T^2 + 6.71615396063011\,T - 33.3332520604835$$

$$Growth_{large} = -0.0000672313797313931\,T^4 + 0.00557547313797499\,T^3 - 0.169902396214982\,T^2 + 2.30515956959863\,T - 11.8629876373727$$

$where\ T = monthly\ average\ SST\ over\ 25\ years\ and\ growth\ is\ in\ term\ of\ grams\ per\ week$

Shrimp growth was modeled weekly, as shrimp in different size classes grow at different rates as determined by the equations we derived above. As explained in the “Revenue Data” section above, temperature utilized in the calculations corresponded to average monthly sea surface temperatures over a 25 year period for each cell designated in GIS. Weekly growth rates were incorporated into the MATLAB model to calculate average shrimp size every week, using the following algorithm:

$$If\ Average\ Weight\ Shrimp\ in\ week\ w < 10.8g, use\ Growth_{small}$$
$$If\ Average\ Weight\ Shrimp\ in\ week\ w \geq 10.8g\ and < 16, use\ Growth_{med}$$
$$If\ Average\ Weight\ Shrimp\ in\ week\ w \geq 16g, use\ Growth_{large}$$

This algorithm dictated that the correct growth function for each week be selected based on the appropriate size category of shrimp for that week. Growth rate was modeled independently of feed intake, as we assumed that the shrimp were fed adequately so that feed was not a limiting factor on growth.

Shrimp Pricing

Once we calculated the final average weight of our shrimp, we determined the ex-vessel shrimp price per kilogram by referencing the appropriate shrimp size class category. The total harvest biomass was assigned a price based on the average head-on shrimp weight at harvest.

## Costs

Total costs in an Aquapod production system consist of capital startup costs, operational costs, and costs associated with risk.

$$Total\ Cost = Capital\ Costs + Operational\ Costs + Risk\ Costs$$

### Capital Costs

Capital costs are comprised of the cost of the Aquapod itself, installation fees, the cost of boats to service the Aquapod, the cost of diving equipment, and permitting fees, as summarized in Table 4.

**Table 4. Capital costs values and sources.**

| Capital Costs | Value | Source |
|---|---|---|
| Micropod | $21,625 | Ocean Farm Technologies |
| Installation | $1,000 | Ocean Farm Technologies |
| Boats | $40,000 | Pesquera Delly |
| Dive Gear | $1,200 | Ocean Farm Technologies |
| Concession | $1,000 | NOS |

Micropods, which are the Aquapod type used in our artisanal model, are currently priced at $21,625 each, with an installation fee per pod of $1,000 determined by Ocean Farm Technologies engineers. In our model, we also assume that two boats are needed to service the nine-pod array. Dive gear has been estimated to cost $1,200 per diver based on Pesquera Delly's Aquapod trial operations. These capital costs are only incurred during year one of Aquapod operations, as they are one-time fixed costs.

A Concession, or permit, must be granted by SEMARNAT or SAGARPA, Mexican governmental agencies, before Aquapod operations can begin in the ocean. Concessions prices are variable, yet NOS estimated the costs to be $1,000 per site. The cost of a Concession is primarily an upfront cost, but a nominal renewal fee is required to maintain control of the site. To account for this, we incorporated an annual cost of $100 into our model for years two through twenty.

### Operational Costs

Operational costs were complied by observing Pesquera Delly's Aquapod operations in Guaymas. Operational costs consist of stocking of the post-larvae, compressed air for SCUBA tanks and feed, maintenance, travel and labor costs. These costs are composed of price data (e.g., fuel prices), the amounts of inputs (e.g., amount of feed), and the spatial parameters that affect cost (e.g., the location and distance to the nearest launch sites). Table 5 summarizes the variables and their respective sources that were taken into consideration in calculating the operational costs of running an Aquapod operation:

**Table 5. Operational costs inputs, prices (where applicable), and data sources.**

| Operational Cost Parameters | Price (USD) | Source |
|---|---|---|
| Post-larvae price ($/ gram) | $0.01 | Pesquera Delly |
| Fuel Economy Boat 1 ($/liter) | $0.60 | Field Research |
| Fuel Economy Boat 2 ($/liter) | $0.30 | Field Research |
| Feed ($/kg) | $1.20 | P.I.A.S.A./ Pesquera Delly |
| Dive gear maintenance (per day) | $0.60 | Ocean Farm Technologies |
| Sea-Surface Temperature (degrees C) | Spatially variable | TNC-COBI |
| Distance to Launch Sites (km) | Spatially variable | Google Earth (KML file) |
| Air ($/tank) | $4.00 | Ocean Farm Technologies |
| Diver Wage ($/hour) | $10.00 | Pesquera Delly |
| Divers (#/day) | 7 | Pesquera Delly |
| Stocking Density (post-larvae/$m^3$) | 400 | Pesquera Delly |
| Price of Fuel ($/liter) | $0.68 | Field Research |
| Air Tanks (#/day) | 14 | Field Research |

Further explanation of some of these variables is included below:

- Post-larvae costs consist of the amount of post-larvae stocked (determined by our stocking density) multiplied by the price of post-larvae per unit weight
- Fuel is a direct function of the boat fuel economies used in the model, fuel price, and total roundtrip distance traveled from the nearest launch site to the Aquapod. We utilized Google Earth to determine viable launch sites which were defined as ports, marinas, or sandy beaches with road access. Both the Micropods and the boats that service them can be launched from any accessible port, marina or beach. Using this definition, we identified and sited launch sites within our three study areas, as applicable. The Google Earth KML files were converted into shapefiles for use in GIS. In GIS, we then used the "Euclidian Distance" tool to calculate the distance from each cell

within the suitable area to the nearest launch site. As with temperature, this spatial distance to launch site data was then exported to Excel for use in the MATLAB model.

- Compressed air is used daily by the divers to maintain the Micropods and feed the shrimp. Total cost of compressed air depends both on the cost of one tank and the number of tanks used per day.
- Feed cost is a function of the amount of feed applied (which, in our model, is a function of temperature—see below), and the price of feed.
- Dive gear maintenance involves repairing or replacing dive gear due to wear and tear, and is represented as a daily average cost.
- Dive costs in our model are a function of the number of divers, their wage and the number of hours worked per day. Hours worked were based on a 6 hour day plus travel time, which is dictated by the distance from launch sites. Divers were assumed to work 355 days out of the year, as the Aquapods need to be serviced even when they are not in a harvest cycle.
- Labor represents the current wage divers may receive for operating on the pods.

Feed application is a production cost that is dictated by shrimp metabolism. We developed a feed model based on temperature as a proxy for shrimp metabolism using the Wyban, et al. (1995) data that we had previously utilized to model growth rates. Based on our model, the shrimp demand a certain percentage of their body weight in food each week, based on their size (small, medium or large) and the temperature of the water, in order to maintain their growth rate, as dictated by the following equations:

$$Feed_{small} = .07 * (-0.025\,T^2 + 1.675\,T - 19) * Biomass_w$$
$$Feed_{med} = .07 * (-0.00955\,T^2 + .7762\,T - 9.6143) * Biomass_w$$
$$Feed_{large} = .07 * (4e^{-16}\,T^2 + .2\,T - 2.5) * Biomass_w$$

*Where T=monthly average temperature over 25 years*

We calculated the correct amount of feed demanded by the shrimp each week using the following algorithm in our MATLAB model:

$$If\ Average\ Weight\ Shrimp\ in\ week\ w < 10.8g, use\ Feed_{small}$$
$$If\ Average\ Weight\ Shrimp\ in\ week\ w \geq 10.8g\ and < 16, use\ Feed_{med}$$
$$If\ Average\ Weight\ Shrimp\ in\ week\ w \geq 16g, use\ Feed_{large}$$

Risk Costs

There are various forms of risks associated with Aquapod operation in the open ocean, and therefore we have captured these risks as expected costs in our Aquapod production system. Based on consultation with our client, current Aquapod operators, Ocean Farm Technologies and other experts, we identified four possible sources of risks associated with Aquapod operation:

1. Damage from ship strikes
2. Damage from storm events
3. Shrimp mortality due to disease transmission from existing aquaculture
4. Shrimp mortality due to contamination from pollution sources

Each risk was assigned a probability of occurrence at d=0, directly adjacent to the maximum potential risk, as well as a distance or depth at which the probability of occurrence was half that of the d=0 value. These values were based on literature review and expert consultation (Administracion Portuaria Integral, n.d.; C. Goudey, personal communication, Jan 18 2011; Meyer, 1991; Offshore Aquaculture Consortium, 2005; Umesh et al., 2008; Wang et al., 2005). Additional research should be conducted to refine these values, however, as there is still a lot of uncertainty inherent in the assigned probability and distance/depth pairings. We assumed that risk decays exponentially from the source, and we used the half-life equation to describe these risks at any given distance (d) from the risk:

$$\rho_t = \rho_o * 2^{-\frac{d}{d_{\frac{1}{2}}}}$$

*Where $\rho_0$ equals the risk of a given threat at the source of the threat, d is the distance from the threat, and $d_{1/2}$ is the distance at which there is half the chance of the threat event happening.*

While the specific values in the following risk equations have a lot of uncertainty associated with them, we are confident in the basic assumption that risks are higher closer to threats, and decay exponentially as moving farther from the threat. These risk models provide important insight into the relative risks between potential Aquapod deployment sites.

The spatial parameters that affect risk first had to be calculated and compiled in GIS and then exported to an Excel table for use in our model. Several partners provided us with some spatial input data, while other spatial input data were generated using Google Earth. The sources and format for each data layer at each site are summarized in Table 6.

**Table 6. Source and format (in parentheses) for risk model spatial input data at each site; CIBNOR is the Centro de Investigaciones Biológicas del Noroeste; TNC/COBI is a partnership between The Nature Conservancy and Comunidad Y Biodiversidad.**

| Data Layer | La Paz | Guaymas | Magdalena Bay |
|---|---|---|---|
| Bathymetry[6] | Site-Suitability Model (raster) | Site-Suitability Model (raster) | Site-Suitability Model (raster) |
| Shipping Lanes [7] | Site-Suitability Model (raster) | Site-Suitability Model (raster) | N/A |
| Existing Shrimp Aquaculture | CIBNOR (polygon shapefile) & Google Earth (KML file) | Google Earth (KML file) | Google Earth (KML file) |
| Point Source Pollution | Google Earth (KML file) | Google Earth (KML file) | Google Earth (KML file) |

While we received some data on existing shrimp aquaculture in La Paz from CIBNOR, we again generated additional data using Google Earth. For this step of preparing data for the spatial bio-economic model, existing shrimp aquaculture was defined as terrestrial aquaculture ponds visible in Google Earth. We focused only on terrestrial aquaculture because we were interested in modeling the risk of disease transmission from existing shrimp aquaculture. Existing shrimp aquaculture occurs only on land in this part of the world, with one exception: the offshore Aquapod trial in Guaymas, which was also included as an existing shrimp aquaculture site in this step.

There is one assumption implicit in this definition: all terrestrial ponds visible in Google Earth contain shrimp aquaculture. We had to make this assumption in order to model disease transmission risk spatially because there were no data available that differentiated the different terrestrial ponds by type of aquaculture. According to expert opinion and local knowledge (CIBNOR scientists, personal communication, June 8, 2010), this assumption is reasonable for our three study areas, as most, if not all, of the terrestrial aquaculture in these regions *is* shrimp aquaculture. It is possible, however, that there are a few terrestrial aquaculture ponds included in our existing shrimp aquaculture layer that actually contain other types of aquaculture. Even if there are some occurrences of non-shrimp aquaculture, however, assuming all the terrestrial aquaculture to be shrimp is still a conservative assumption, as the risk of disease transmission from non-shrimp aquaculture sites (e.g., finfish, shellfish) is likely lower than that from shrimp aquaculture sites.

---

[6] See Site-Suitability Methodology section for derivation of the bathymetry data layers.
[7] See section Site-Suitability Methodology for derivation of the shipping lane data layers.

In addition to the aquaculture layer, we also used Google Earth to generate point source pollution and launch sites layers. Point sources of pollution were defined as river mouths and industrial facilities with effluent clearly visible in Google Earth. For this step, we assumed that all pollution has the same effect on risk of shrimp toxicity. While river mouths and industrial plants tend to have different types and amounts of pollutants, we had no way of identifying specific contaminants in a spatial context with available data. Therefore, for the purposes of defining pollution sites that could be the source of risk, all pollution sites were treated equally. As with our assumptions for terrestrial aquaculture, this is a conservative assumption for Aquapod siting.

Using these definitions we used Google Earth to identify the various risk sources within our three study areas, as applicable. The Google Earth KML files were converted into shapefiles for use in GIS. In GIS, we then used the "Euclidian Distance" tool to calculate the distance from each cell within the suitable area to the various risk sources. As with temperature and launch sites, this spatial distance to risk data was then exported to Excel for use in the MATLAB model.

## Risk of an Aquapod Ship Strike

One of the risks that should be taken into account in Aquapod marine spatial planning is the risk of a ferry, tanker, or container ship hitting one of the Aquapods. In order to address this risk, we developed an equation to account for the increased risk of placing an Aquapod in close proximity to a shipping lane. For this risk model, we assume there is a 1 percent risk of an Aquapod being struck by a ship at zero kilometers from the edge of the shipping lane, and a 0.5 percent risk of an Aquapod ship strike at 1.5 kilometers from the edge of the shipping lane. Inputting these assumptions into the half-life equation specified above, we can model the probability of an Aquapod ship strike ($\rho_{sl}$) as a function of distance from the shipping lane in kilometers ($d_{sl}$):

$$\rho_{sl} = .01 * 2^{-\boldsymbol{dsl}/1.5}$$

The costs associated with risk of being struck by a ship are a function of the cost of the Aquapod system itself and the profits from the shrimp inside of the pods, because irreparable damage to the pod would likely occur and shrimp would likely be lost in the event of a ship stike. Since shrimp are only in the Aquapods during a portion of the year, we included the probability that there will be shrimp in the Aquapods ( $\frac{2t}{365}$) at the time of a ship strike. We also assume that only the individual Aquapod stuck by the ship is affected by the accident, as opposed to the entire nine-pod array. We therefore divide revenue (R) by the number of Aquapods (Np), since revenue is aggregated across all Aquapods in the array within our model. The equation for expected cost due to risk of a shipping lane strike ($\mathrm{EC_{sl}}$) is as follows:

$$\mathrm{EC_{sl}} = \rho_{sl} * \left(\mathrm{C_{aq}} \ + \frac{2\mathrm{t}}{365} * \frac{\mathrm{R}}{\mathrm{N_p}}\right)$$

*where $C_{aq}$ is the total cost of Aquapod installation and where t equals time in days, R is revenue and $N_p$ is the number of pods in the array at the time of ship strike*

## Risk of Cage Damage from Storm Events

Major storm events may cause damage to the Aquapod cages if wave action is great enough to cause the Aquapods to hit the seafloor. The risk of cage damage is therefore greater if the Aquapod operation is sited in shallower water. To assess this risk, we developed an equation to assess the risk of placing Aquapods at shallower depths. For this risk model, we assume that here is a two percent probability of damage at 15 meters depth, and a one percent probability of damage at 30 meters depth. Inputting these assumptions into the half-life equation, we can model the risk of cage damage ($\rho_{sd}$) from storm events as a function of depth in meters (d):

$$\rho_{sd} = .02 * 2^{-\boldsymbol{d}/30}$$

The cost associated with cage damage from a storm is a function of total Aquapod cost and the profits from the shrimp inside the pods. We assumed that all Aquapods would be lost in a severe storm event, so the cost of an Auapod is multiplied by the number of Aquapods in the array. We also assume that all shrimp revenue will be lost due to escapement or mortality after damage to the cage. The equation for expected cost due to risk of cage damage ($\mathrm{EC_{sd}}$) is as follows:

$$\mathrm{EC_{sd}} = \ \rho_{sd} * \left(\mathrm{C_{aq}} * \mathrm{N_p} + \frac{2\mathrm{t}}{365} * \mathrm{R}\right)$$

*where $C_{aq}$ is the total cost of Aquapod installation, $N_p$ is the number of pods in the array, t equals time in days, and R is revenue*

## Risk of Shrimp Loss from Disease Transmission from Existing Aquaculture

Existing pond aquaculture facilities emit a significant amount of effluent into surrounding waters; therefore, the risk of disease transmission is greater if Aquapods are placed closer to these existing aquaculture facilities. To assess this risk, we developed an equation to assess the risk of placing Aquapods closer to existing aquaculture operations. For this risk model, we assume there is a 30 percent chance of disease outbreak with 100 percent mortality at zero kilometers from the ponds, and a 15 percent chance of disease outbreak with 100 percent mortality at one kilometer from the ponds. Inputting these assumptions into the half life equation specified above, we can model the risk of disease from existing aquaculture ($\rho_d$)as a function of distance from the existing aquaculture operation in kilometers ($d_{aq}$):

$$\rho_d = .3 * 2^{-\boldsymbol{daq}/1}$$

We assume that if a disease outbreak occurs, it will result in 100 percent mortality of the shrimp for that harvest cycle, resulting in a loss of half of the total revenue that year. The expected cost associate with the risk of being closer to existing aquaculture farms ($\mathrm{EC_d}$) is given by the equation:

$$\mathrm{EC_d} = \rho_d * \frac{\mathrm{R}}{2}$$

*where* $\frac{R}{2}$ *equals the revenue in one harvest*

### Risk of Shrimp Loss from Proximity to Pollution Sources

Pollution sources, such as river outflows and industrial facilities, may contain toxic materials, which pose a threat to shrimp health. To assess this risk, we developed an equation to assess the risk of placing Aquapods closer to potential sources of pollution. For this risk model, we assume that there is a 20 percent chance of pollution resulting in 20 percent mortality at zero kilometers from the pollution source, and a 10 percent chance of pollution resulting in 20 percent mortality at one kilometer from the pollution source. Inputting these assumptions into the half life equation specified, we can model the risk of shrimp loss from pollution as a function of distance from pollution point sources in kilometers ($d_{ps}$):

$$\rho_{ps} = .2 * 2^{-\boldsymbol{dps}/1}$$

As specified in the assumptions, we assume that pollution will cause a 20 percent loss of shrimp, resulting in a 20 percent reduction in revenue for one harvest that year. The expected cost associated with the risk of being closer to a pollution source is given by the equation ($\mathrm{EC_{ps}}$):

$$\mathrm{EC_{ps}} = \rho_{ps} * .2 * \frac{\mathrm{R}}{2}$$

*where* $\frac{R}{2}$ *equals the revenue in one harvest*

## Evaluating Net Present Value

With the total revenues and total costs both modeled, the next step was to determine the profitability over a given number of years. To account for the time value of money, we chose a discount rate (r) of five percent to calculate the net present value (NPV) of an Aquapod operation.

$$Profit_y = TotalRevenue_y - TotalCost_y$$

Therefore, NPV (USD) after (y) years of operation is equal to

$$NPV = \sum_{0}^{y} \frac{Profit_y}{(1+r)^y}$$

## Addressing Uncertainty

Because the Aquapod is a relatively new and untested technology, there were minimal data available on exact operational costs and expected yield in such a system. As seen in some of the previous tables, several parameters were represented as a range of numbers. Our parameter ranges were developed from the best information available. Some production parameters were gathered from the Pesquera Delly pilot project in Guaymas. However, access to reliable information from this trial project was limited. Through consultation with scientific and industry experts, we were able to define the minimum and maximum possible values for our parameters (Table 7).

We then addressed this uncertainty by running a Monte Carlo simulation over 1000 iterations. We programmed the model to randomly select parameter values for each iteration that fell within our defined boundaries. Over the 1000 iterations, our spatial bio-economic model generated a distribution of possible NPVs at every location. We then averaged these 1000 NPVs for each location to generate a spatially explicit expected NPV (ENPV). We did not include the risk probabilities in this Monte Carlo analysis, as we were not able to obtain a range for the parameters that we were confident in based on the information available. Further data collection and research could improve confidence in these variable ranges, and they should be included in future iterations of our spatial bio-economic model.

**Table 7. Monte Carlo analysis variable estimates and ranges.**

| Monte Carlo Parameters | Estimate | Minimum | Maximum |
|---|---|---|---|
| **REVENUE** | | | |
| Price (per size class; see Table 3) (USD/kg) | Size class estimate | Size class minimum | Size class maximum |
| Mortality Coefficient | 0.01 | 0.001 | 0.01 |
| **CAPITAL/FIXED COSTS** | | | |
| Dive Gear (USD) | $1200 | $800 | $2000 |
| Concession Cost (USD) | $1000 | $500 | $2000 |
| **VARIABLE COSTS** | | | |
| Number of Divers (#) | 7 | 6 | 8 |
| Diver Wage (USD/hr) | $10.00 | $5.00 | $12.00 |
| Feed Price (USD/kg) | $1.20 | $0.60 | $1.80 |
| Fuel Economy Boat 1 (km/L) | 0.6 | 0.4 | 0.8 |
| Fuel Economy Boat 2 (km/L) | 3 | 2 | 4 |
| Air Tanks (tanks/day) | 14 | 12 | 18 |
| Stocking Density (pl/$m^3$) | 400 | 200 | 600 |
| Post Larvae Price (USD/pl) | $0.01 | $0.005 | $0.02 |
| Dive Gear Maintenance (USD/day) | $0.80 | $0.60 | $1.00 |
| Price of Fuel (USD/L) | $0.68 | $0.50 | $1.00 |

## Visually Displaying Spatial Profit Data

Once we had added the ENPV for each cell to the spatial coordinates table, we imported the table back into GIS by using the "Add XY Data" tool and the latitude and longitude coordinates of the original cells. The spatial profit data were then converted into a "feature points" shapefile of ENPVs per site to display the spatial profit data in map form.

## Industrial Model

As outlined in the "General Approach" section above, we modified the artisanal Micropod model that we first developed in order to create a model that represents a larger industrial park operation. Using the same foundation we used for the artisanal model facilitated cross-model comparison. The spatial bio-economic model for the industrial model differed from the artisanal model in the breakdown of revenue and costs due to the larger pod size and the differences in the business model.

On the costs side, in the industrial business model, the operators use a trawler, a platform boat, and a panga to service an array of sixteen A-7000 Aquapods. Consequently, all major capital costs increase significantly relative to the artisanal model, due to the nature of the business model (Table 8). Due to the deeper mooring depths in the industrial model, occasional mooring maintenance would require the use of an ROV, but regular feeding and maintenance are still performed by divers. Note that dive gear costs remain the same per person but total dive gear cost will more than double due to an increase in the number of divers.

**Table 8. Difference in capital costs between artisanal and industrial models.**

| Capital Costs | Artisanal Cost | Industrial Cost |
|---|---|---|
| Micropod/Aquapod | $21,625 | $300,000 |
| Installation | $1,000 | Included in pod cost |
| Boats | $40,000 | $340,000 |
| Dive Gear | $1,200/diver | $1,200/diver |
| Concession | $1,000 | $1,000 |
| ROV | N/A | $50,000 |
| Scuba Tanks | N/A | $10,000 |

In addition to the changes made in upfront capital costs, we altered operational costs to more accurately represent the industrial business model. Table 9 summarizes how the operational costs vary between the two models.

**Table 9. Differences in operational costs, inputs, and prices (where applicable), between the artisanal and industrial models.**

| Operational Cost Parameters | Artisanal Price | Industrial price |
|---|---|---|
| Post-larvae price (USD/ gram) | $0.01 | $0.01 |
| Fuel Economy Boat 1 (USD/liter) | $0.60 | $0.60 |
| Fuel Economy Boat 2 (USD/liter) | $0.30 | $0.30 |
| Feed (USD/kg) | $1.20 | $1.20 |
| Dive gear maintenance (USD/day) | $0.60 | $0.60 |
| Sea-Surface Temperature (degrees C) | Spatially variable | Spatially variable |
| Distance to Launch Sites (km) | Spatially variable | Spatially variable |
| Air (USD/tank) | $4.00 | N/A |
| Diver Wage (USD/hour) | $10.00 | $10.00 |
| Divers (#/day) | 7 | 16 |
| Stocking Density (post-larvae/$m^3$) | 400 | 400 |
| Price of Fuel (USD/liter) | $0.68 | $0.68 |
| Air Tanks (#/day) | 14 | N/A |
| Trawler Operation (USD/day) | N/A | $100 |
| Storage Facility Cost (USD/year) | N/A | $25,000 |

The most significant changes to operational costs in the industrial model are summarized below:

- Fuel costs are dependent on distance from launch sites, and in this model, launch sites were defined as ports or marinas, since the larger A-7000s require cranes and other technical support that would not be available in the beach launch sites used in the artisanal Micropod model.
- The number of divers has roughly doubled, thus doubling the overall dive costs including total dive gear and diver salaries
- A trawler will be stationed on site and therefore is not incorporated into travel costs but does cost $100/day to operate
- The trawler's compressor will fill tanks and the cost of air is included in the cost of operation the trawler
- The cost of feed and stocking density remains the same, however total cost of feed and stocking will increase because the total volume is much higher due to the increase in the volume of the A-7000s relative to the Micropods, as well as an increase in the number of pods (16) in the industrial model versus the artisanal model (9).
- In order to manage the enormous amount of feed and equipment required in the industrial model, we included a storage facility in the costs.

In addition to the operational costs listed above, overhead costs will also increase. Table 10 summarizes the costs for the additional personnel needed to run the industrial operation.

**Table 10. Additional personnel costs and data sources.**

| Employee Position | Cost | Source |
|---|---|---|
| Site Manager (USD/year) | $56,000 | (http://www.indeed.com/salary/q-Manager-l-Mexico,-MO.html) |
| Half-time Accountant (USD/year) | $9,000 | (http://www.worldsalaries.org/accountant.shtml) |
| Lead diver (USD/hour) | $15 | Pesquera Delly |
| Two Night Watchmen (total USD/year) | $41,000 | Field Research |
| Mechanic (USD/year) | $38,000 | (http://www.simplyhired.com/a/salary/search/q-marine+mechanic) |

For this industrial model, we made several clarifying assumptions: (1) the divers needed to operate the A-7000s will be of the same technical level as those needed to operate the Micropods and will therefore require the same wage; (2) stocking densities, growth rates and mortality rates remain consistent between the two different sizes of Aquapods; (3) no economies of scale exist with respect to costs (e.g., feed price, post-larvae price and cost of dive gear) in the larger A-7000s.

In the artisanal model, the cell size (300 x 300 meters) is dictated by the smallest area that could accommodate the nine pod array and the spacing between each Micropod is about 100 meters to ensure that pods do not run into each other. In the industrial model, however, spacing between the A-7000s requires an additional 40 meters due to the difference in pod diameter. The industrial model differs also in the configuration of pods. The artisanal model is set up as a grid of nine pods, but the industrial model (see Figure 10) requires a hollow, doughnut-like configuration to allow more accessibility for the trawler when stocking and harvesting shrimp. Due to this required spacing and configuration, the minimum cell size for the industrial model is 700 x 700 meters.

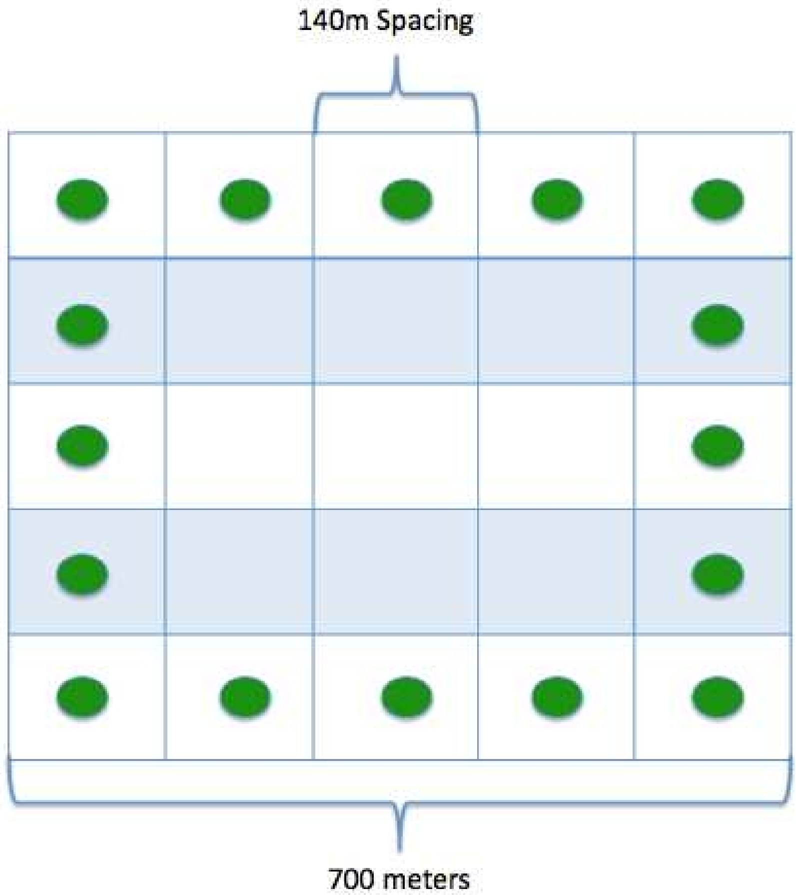



**Figure 10. A schematic of the layout of A-7000s for the industrial model.**

## Step 3. Sensitivity Analyses

### Elasticity Analysis

Having determined the spatial variance in profitability of Aquapods in a given region, we next examined which parameters most impacted profitability. To evaluate this sensitivity, we performed a spatially independent elasticity analysis on the non-spatial variables in our spatial bio-economic model, as well as on feed and fuel costs. Feed costs are spatially correlated because the amount of feed required in our model is dependent on temperature (a spatial variable). Similarly, the amount of fuel used is a factor of the potential operation site's distance from the nearest launch site. Thus, we controlled for spatial variability by assessing model elasticity at one site, which holds temperature and distance to launch sites constant. This approach gives us an estimate of the elasticity of these spatial parameters, though we acknowledge there could be some degree of variation in the elasticity of feed and fuel costs between sites with different temperature and distance to launch sites values.

In performing our elasticity analysis, we wanted to examine how a one percent independent change in one of our input parameters would change ENPV. To conduct this analysis, we began by calculating a baseline ENPV, which we determined by running our bio-economic equation using the average value of each parameter range. ENPV was then recalculated for an independent one percent increase of each parameter of interest. The resulting percentage change in ENPV from each one percent increase of a parameter value generated the elasticity value (E) for that parameter, as given by the following equation:

$$E = \frac{\%\Delta ENPV}{1\%\ \Delta parameter}$$

### Parameter Value Range Sensitivity Analysis

The amount that profit (or NPV) varies due to each parameter is a function of the combined effect of both the elasticity of profit to that parameter and the amount of uncertainty in NPV that the parameter ranges create. In order to examine the effect of the parameter value ranges on uncertainty in NPV, we also performed a parameter value range sensitivity analysis. This analysis is complementary to the elasticity analysis, which makes our overall sensitivity analysis more robust. Figure 11 demonstrates how a parameter with a high elasticity, but a small parameter value range (parameter A), will result in a smaller total profit range than a parameter that has a low elasticity and a large parameter value range (parameter B).

Evaluating the relative sensitivity of model profits to these parameters based solely upon our elasticity analysis may result in a false conclusion that parameter A is more important than parameter B in terms of research priorities. Finding better information for the value range of parameter B, however, and thereby reducing the large spread of parameter B's total potential profit range, could also be an important research priority.

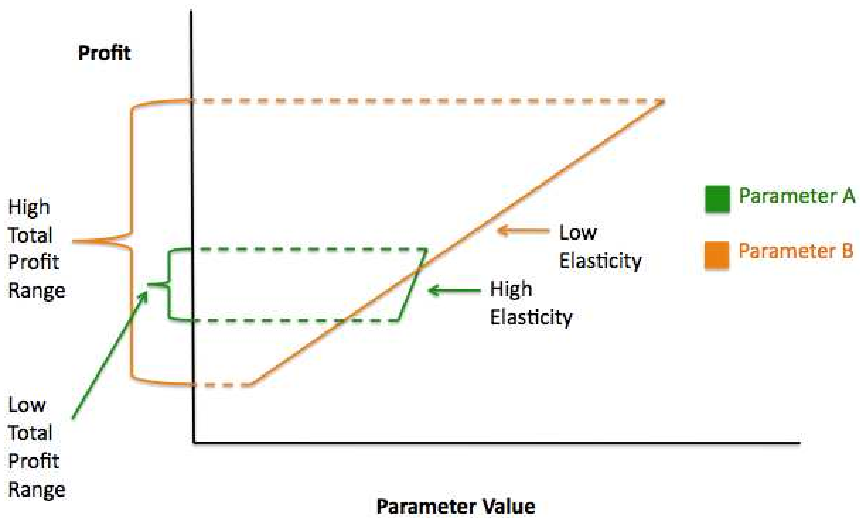



**Figure 11: Demonstration of the difference between the elasticity analysis and the parameter value range sensitivity analysis.**

As with our elasticity analysis, we first calculated the average of the range for each parameter we wished to test. Holding all parameters at their average except for the one we were testing, we ran the model for both the minimum and maximum value within that parameter's range. We then calculated the difference in NPV's to obtain the total profit range for that parameter, and ranked the parameters in terms of that total profit range.

## Results and Discussion

### Site-Suitability Analysis

We modeled site-suitability for the artisanal shrimp model at all three sites, while we modeled site-suitability for the industrial model in La Paz only. A summary of the site-suitability results for both models follows.

#### La Paz

As shown in Figure 12, approximately seven percent of the La Paz study area is suitable for Micropod siting. Footprints of the existing shipping lanes (leading out of La Paz and Pichilingue) and existing offshore aquaculture pens (the three rectangular cutouts within the viable zone) are clearly visible (see Appendix A5 for maps of shipping routes and A4 for maps of existing aquaculture sites in La Paz). There is a marine reserve encompassing the area surrounding Isla Espiritu Santo (the large island to the North of Pichilingue), which also impacted the suitable area.

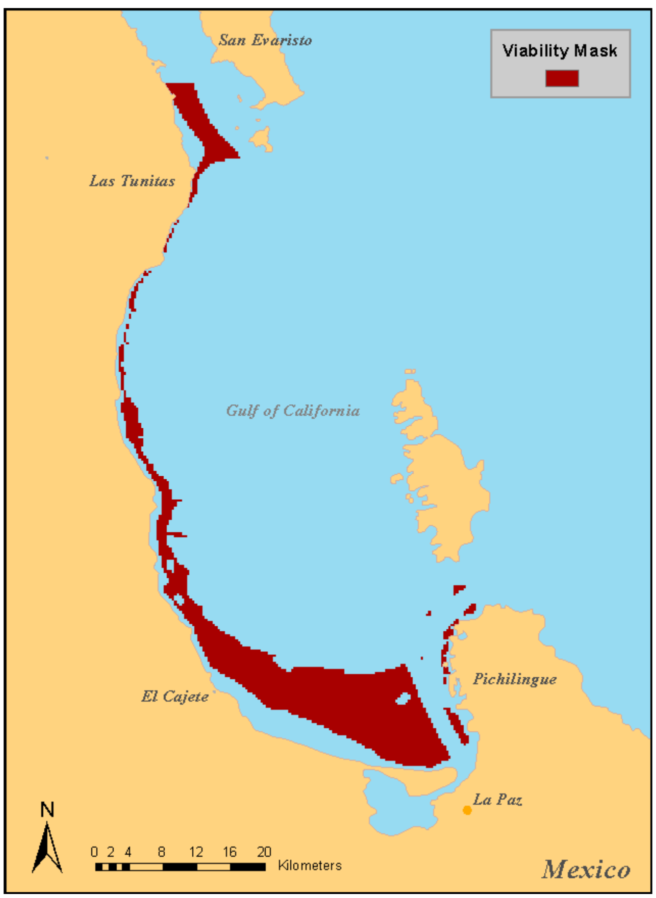



**Figure 12. Map depicting the areas suitable for artisanal model Micropod placement in La Paz.**

In addition to influence of these existing uses, the suitable area was also influenced by the depth and benthic slope fields. We found that for this study site, depth was a more important factor than benthic slope in determining site-suitability: within the region of appropriate depth, the benthic slope was suitable (less than ten percent gradient) in nearly every location (see Appendix A1 and A2 for La Paz depth and slope fields). It should be noted that the portion of the viability mask between Las Tunitas and San Evaristo is less reliable, as there were fewer depth data points in this area and more depths had to be estimated by interpolation.

## Guaymas

As shown in Figure 13, approximately 11 percent of the Guaymas study area is suitable for Micropod siting. We again see that the shipping lane coming out of the Guaymas harbor cut a swath through the otherwise viable zone to the south of the harbor. In contrast to La Paz, however, Guaymas has no marine reserves and only one existing offshore aquaculture site: the Aquapods in the trial being run by


**Figure 13. Map depicting the areas suitable for artisanal Micropod placement in Guaymas.**

Pesquera Delly located to the south of San Carlos. As with La Paz, depth was a more important factor than benthic slope in determining site-suitability (see Appendix A6 and A7 for Guaymas depth and slope fields). It should be noted that the southernmost portion of the viability mask (where the viability mask bulges, narrows to a point and then bulges again) is less reliable, as there were fewer depth data points and more depths had to be estimated by interpolation.

## Magdalena Bay

As shown in Figure 14, approximately 16 percent of the Magdalena Bay study area is suitable for Micropod siting. In this study area, there were no shipping lanes or offshore aquaculture sites and only one marine reserve (located outside the bay in the northwestern-most portion of the map), so site-suitability was driven almost exclusively by depth (benthic slope was again of a suitable gradient within all the areas of suitable depth) (see Appendix A10 and A11 for Magdalena Bay depth and slope fields).

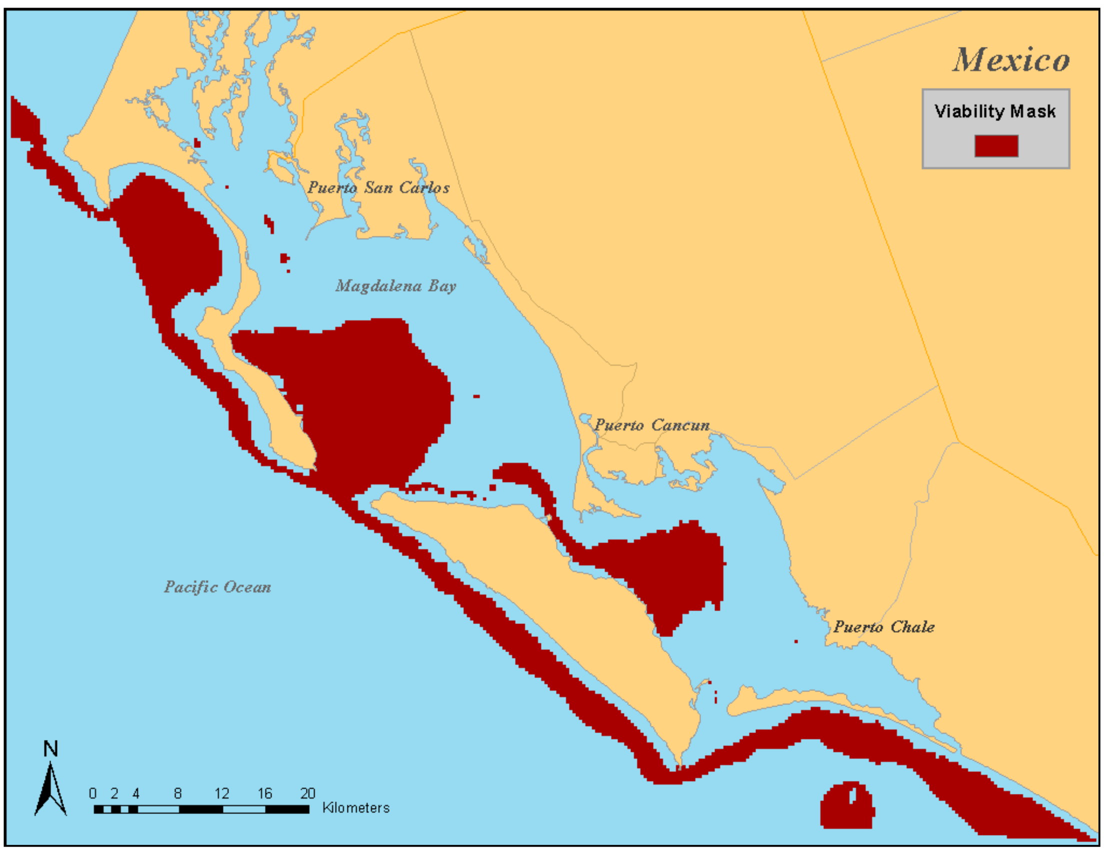



**Figure 14. Map depicting the areas suitable for artisanal Micropod placement in Magdalena Bay.**

It should be noted that Magdalena Bay is a well-known nursery ground for grey whales: large numbers of whales can be found in the bay from January through April. Currently there is no tracking data available for grey whales in Magdalena Bay, yet onsite research to determine common areas of whale congregation could be added to the site-suitability model as a competing use, potentially altering the suitable areas for Aquapod placement.

## La Paz: Industrial A-7000s

As shown in Figure 15, approximately nine percent of the La Paz study area is suitable for industrial model A-7000 siting. Footprints of the existing shipping lanes and existing offshore aquaculture pens are again visible, though the larger cell size for this industrial model results in less clearly defined footprints of these features. As with the artisanal model, we found that for this study site, depth was a more important factor than benthic slope in determining site-suitability (see Appendix A1 and A2 for La Paz depth and slope fields).


**Figure 15. Map depicting the areas suitable for industrial model A-7000 placement in La Paz.**

The viability masks for the industrial and artisanal models do not overlap at all because the suitable depth ranges for Micropods (15-45 meters) and A-7000s (48-150 meters) are mutually exclusive. Consequently, artisanal Micropod businesses and industrial A-7000 parks could both operate in the bay without competing for space. Taken together, the artisanal and industrial Aquapod models could be viably operated in approximately 16 percent of the bay.

## Spatial Bio-Economic Analysis

Using our spatial bio-economic model, we completed analyses of baseline ENPV for all three of our study areas using the artisanal Micropod model. We also assessed ENPV for the industrial model in the Bay of La Paz. Finally, we focused on the La Paz study area as a case study for exploration of additional models and alternative management scenarios. The baseline results for all three study areas are discussed below, followed by a discussion of the ENPV results for the alternative models and adaptive management scenarios.

### La Paz

Figure 16 depicts the baseline artisanal model ENPV for the Bay of La Paz. We see that none of our suitable sites are expected to be profitable under the "business-as-usual" artisanal model, over a 20-year period.

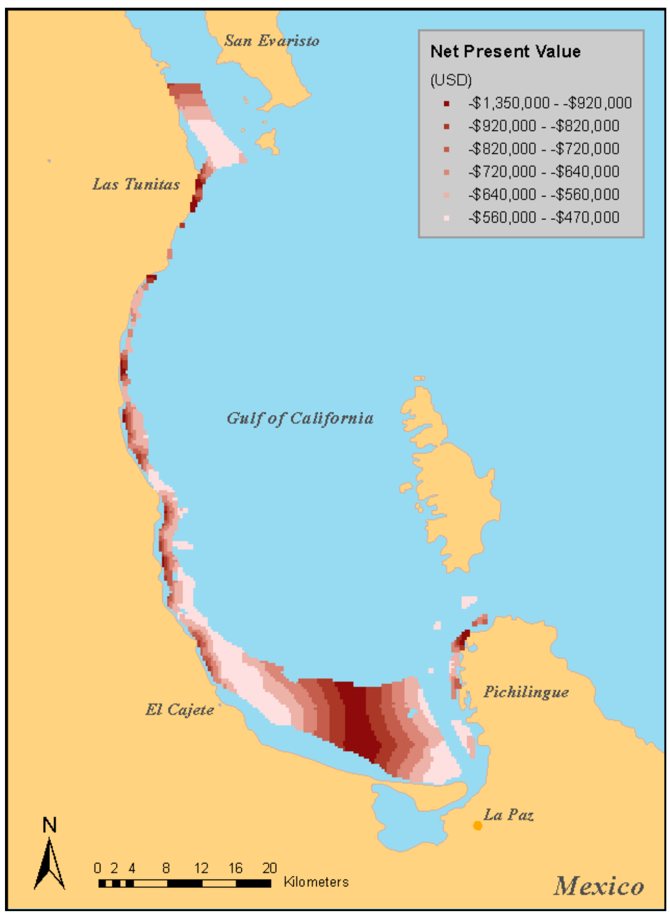



**Figure 16. Map classified with natural breaks to show the distribution of ENPVs across all suitable sites within the Bay of La Paz using our artisanal model. Darker red colors indicate more negative ENPVs.**

Among the suitable sites, we can see the complex interaction of our modeled parameters as they affect profitability or, in this case, lack of profitability. One of the clearest influences is proximity to launch sites. The darkest red area in the bottom central portion of the Bay is the area farthest from launch sites (see Appendix C1) and exhibits the most negative ENPV. As you move shoreward from that area, ENPV generally increases as you get closer to shore, because sites located closer to shoreline launch sites have the advantage of shorter vessel travel times resulting in lower fuel costs.

Upon closer inspection, however, we see that some of the sites closest to shore are also highly negative (e.g., the shoreline area to the north of El Cajete). In some cases, this result is due to the existence of pollution outflows: sites closer to pollution outflows have a higher risk of costs from shrimp mortality, and hence, exhibit more negative ENPVs. In these areas, the potential costs from the risk of pollution mortality outweigh the potential cost savings from being close to a launch site.

While the offshore aquaculture pens hold mainly finfish and hence, pose little disease risk to shrimp, distance to land-based shrimp aquaculture ponds is another risk factor that influences ENPV. In areas where pollution outflows are co-located near shrimp aquaculture sites (as is the case north of Pichilingue),we see that ENPV is even more negative than in areas adjacent to pollution alone (such as the coastline to the north of El Cajete).

Distance to shipping lanes, SST, and depth also all play a role in determining spatial distribution of ENPVs, though these influences are less apparent in the composite map than those of distance to launch sites, aquaculture and pollution outflows. These complex interactions between the six spatial parameters influencing profitability would be impossible to analyze without our comprehensive spatial bio-economic analysis, which demonstrates the value of our approach for both Aquapod owners and coastal managers.

While all of the suitable sites in the Bay of La Paz do exhibit a negative ENPV under the baseline artisanal model, when we look at the range and distribution of those ENPVs (Figure 17), we see that a large portion of the suitable sites are within $500,000 of being profitable. Consequently, different management decisions (e.g., reduction in feed), changes in the model, or reductions in parameter uncertainty could potentially bring a significant portion of the sites into the profitable range.

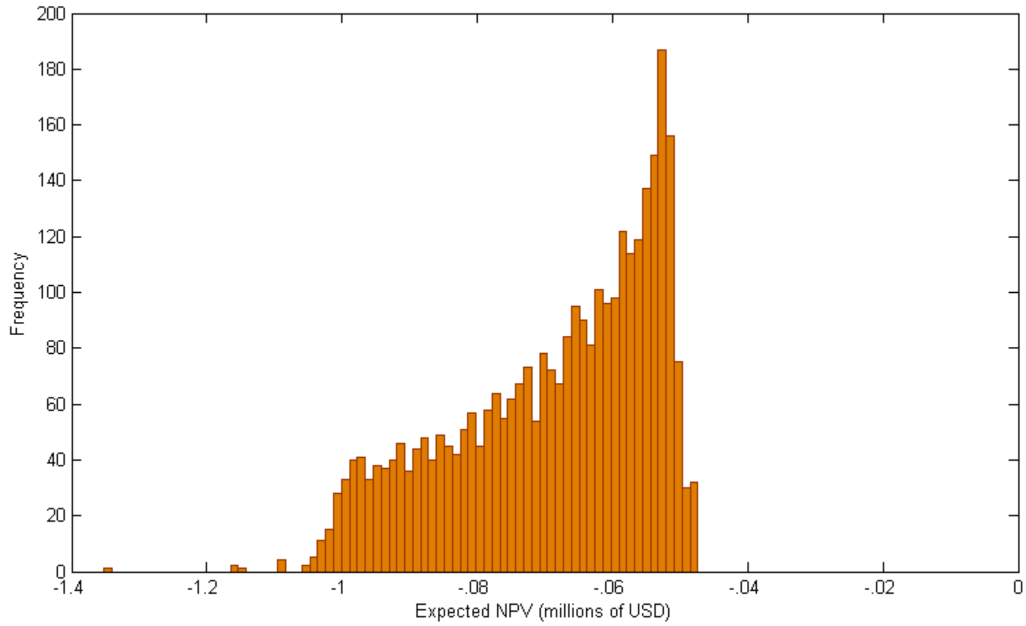



**Figure 17. Histogram depicting the distribution of ENPVs across all sites within the Bay of La Paz using our artisanal model.**

## Guaymas

Figure 18 depicts the baseline artisanal model ENPV for Guaymas Bay. As with La Paz, we see that none of our suitable sites are expected to be profitable under the artisanal model over a 20 year period.

As with the Bay of La Paz, distance to launch sites is one of the primary parameters most influencing profitability in Guaymas. The suitable sites at the southern end of the map are the farthest from potential launch sites and exhibit the most negative ENPVs. We also can see the clear effect of risk of shrimp disease transmission, as evidenced by the less profitable rings surrounding the site of the current trial Aquapods south of San Carlos. Another interesting difference compared to La Paz is the noticeable lack of influence from shoreline pollution outflows. In Guaymas, depth increases at a more gradual rate than it does in the Bay of La Paz. Consequently, sites that are of the suitable depth are farther from shore in Guaymas, where they fall outside the range of pollution influence. This same pattern also applies for land-based shrimp aquaculture sites.

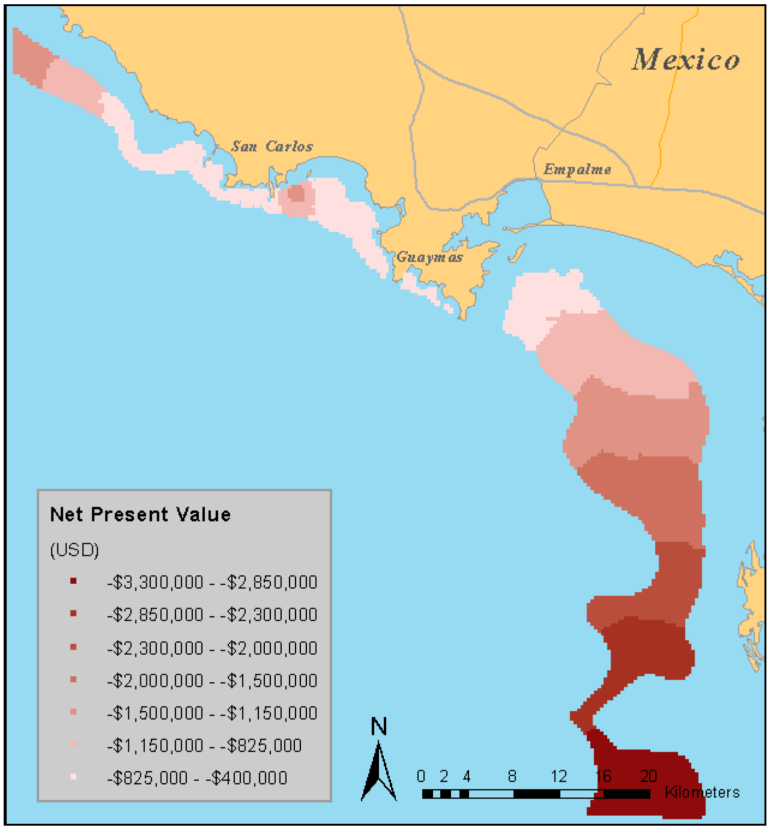



**Figure 18. Map classified with natural breaks to show the distribution of ENPVs across all suitable sites within Guaymas Bay using our artisanal model. Darker red colors indicate more negative ENPVs.**

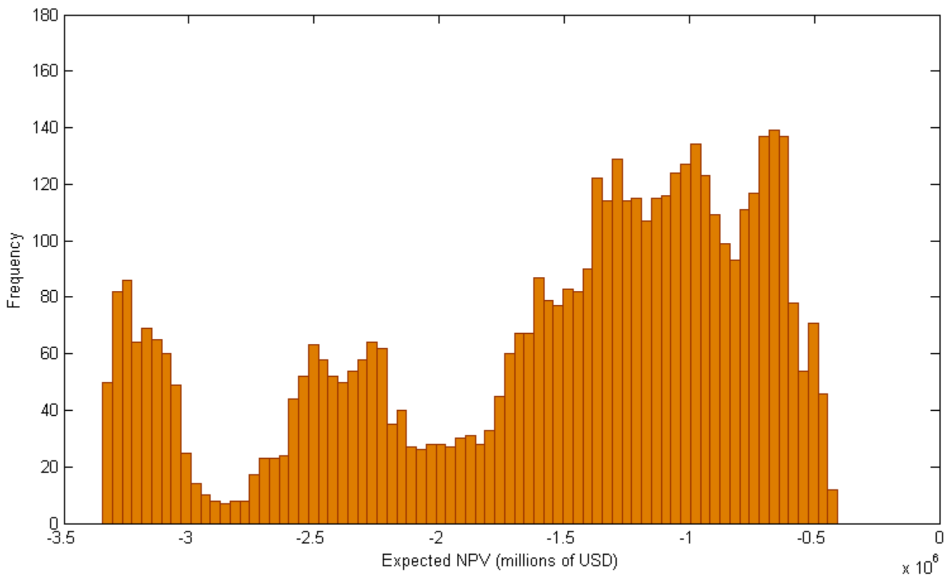



**Figure 19. Histogram depicting the distribution of ENPVs across all sites within Guaymas Bay using our artisanal model.**

When we examine the range and distribution of ENPVs in Guaymas (Figure 19) we see that, in contrast to La Paz, many more of the sites fall in the deeply negative range. La Paz ENPVs ranged from approximately negative $1.3 million to negative $0.4 million. Guaymas ENPVs, however, extend all the way to approximately negative $3.3 million. Clearly, it would be more difficult to generate profitable sites in Guaymas than it would in La Paz.

## Magdalena Bay

Figure 20 depicts the baseline artisanal model ENPV for Magdalena Bay. As with La Paz and Guaymas, we see that none of our suitable sites are expected to be profitable under the artisanal model over a 20 year period. Furthermore, distance to launch sites is again one of the primary parameters most influencing profitability in Magdalena Bay. The suitable sites at the southern end of the map are the farthest from potential launch sites and exhibit the most negative ENPVs. Another interesting feature of the Magdalena Bay ENPV is the influence of sea-surface temperature. Generally, Magdalena Bay is colder than either La Paz or Guaymas because of its location outside the Gulf of California and its resultant exposure to the cold

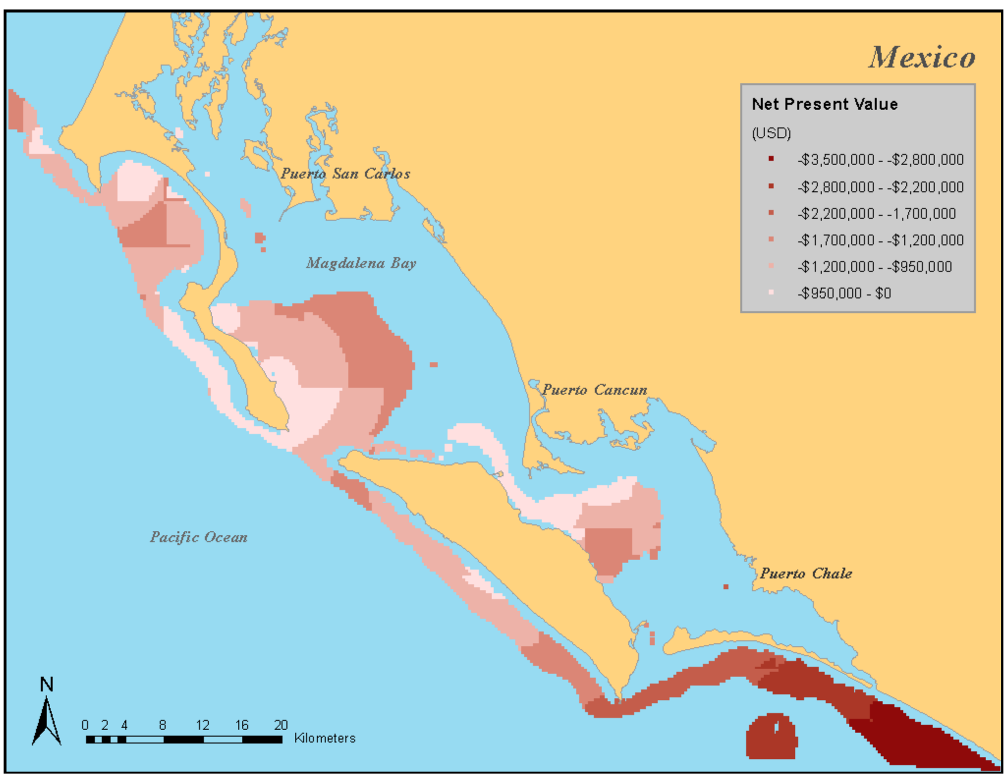



**Figure 20. Map classified with natural breaks to show the distribution of ENPVs across all suitable sites within Magdalena Bay using our artisanal model. Darker red colors indicate more negative ENPVs.**

California Current. Consequently, SST becomes more important in Magdalena Bay. More of the sites fall more frequently into the low end of the shrimp tolerance range for SST, which result in slow growth and extremely low shrimp biomass output. At the same time, lower temperatures mean lower feeding rates, resulting in reduced feed costs. The resultant impact on profitability is apparent in the larger resolution squares of more negative ENPV that are an artifact of the coarser resolution SST data. In most cases, cells within Magdalena Bay with relatively lower temperatures yielded higher NPVs, which means the decrease in feed costs might be compensating for the decrease in growth rates (though this trend does vary by SST month and by site). Regardless, these are just relative differences in profit within the Bay. The overall range of profits is still lower than those in La Paz, partially as a result of the lower range of temperatures in Magdalena Bay.

The range and distribution of ENPVs in Magdalena Bay (Figure 21) are similar to that of Guaymas in that there is a larger range of negative ENPVs, relative to La Paz. Given the colder water temperatures in Magdalena Bay, it may be impossible to generate significantly positive profits with our current artisanal model. One option that might improve profitability potential would be to explore a different species of shrimp that are more tolerant to colder water temperatures, such as blue shrimp (*Litopenaeus stylirostris*), a species native to Magdalena Bay.

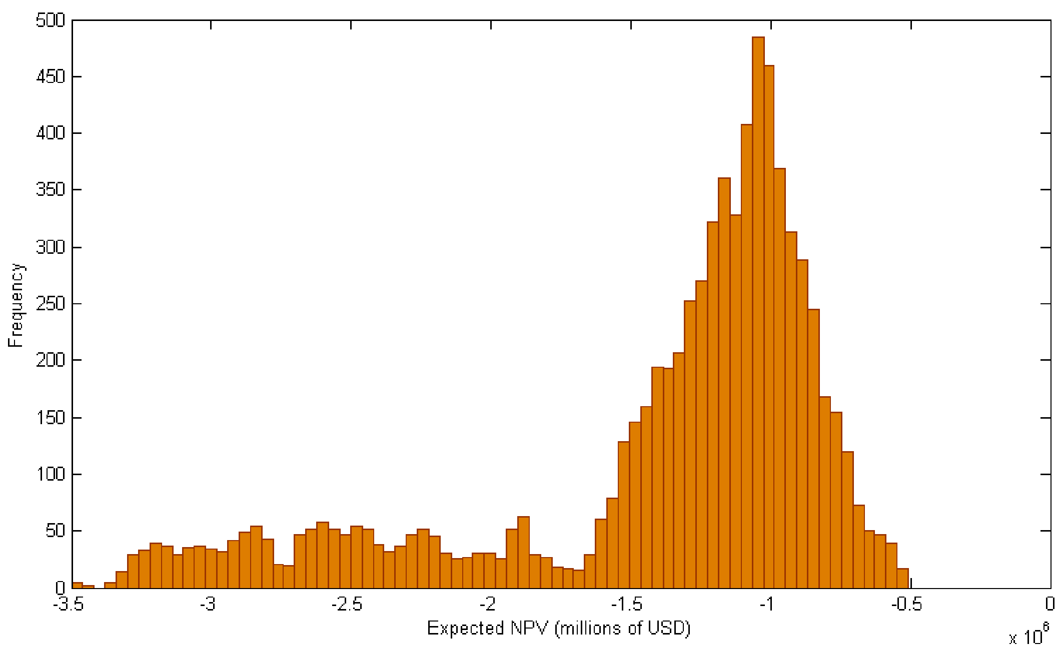



**Figure 21. Histogram depicting the distribution of ENPVs across all sites within Magdalena Bay using our artisanal model.**

## Study Area Comparison

When we look at the profits in all three sites displayed on the same scale (Figure 22), the difference between the sites becomes more apparent. La Paz's least profitable sites fall within the ENPV range of negative 1.5 - 1 million USD, as indicated by the light turquoise color on the maps in Figure 22B. In contrast, both Guaymas and Magdalena Bays have sites with profits as negative as 3.5 million USD, as indicated by the red color in Figure 22A&C. Furthermore, as shown in Table 11, 98 percent of the sites in La Paz are within one million USD of being profitable, while only 31 and 27 percent of Guaymas and Magdalena Bays, respectively, are within one million USD of being profitable. We therefore recommend that Olazul focus the efforts of their initial pilot project in the Bay of La Paz, where it would take relatively smaller gains in ENPV to achieve positive profits in a larger number of suitable sites.

**Table 11. Depiction of the percent of the suitable sites that fall within $0.5 million ENPV classes for each study area.**

| ENPV (millions USD) | Bay of La Paz percent area | Guaymas Bay percent area | Magdalena Bay percent area |
|---|---|---|---|
| -$3.5M to -$3.0M | 0 | 11 | 4 |
| -$3.0M to -$2.5M | 0 | 6 | 7 |
| -$2.5M to -$2.0M | 0 | 12 | 6 |
| -$2.0M to -$1.5M | 0 | 14 | 8 |
| -$1.5M to -$1.0M | 2 | 29 | 48 |
| -$1.0M to -$0.5M | 95 | 29 | 27 |
| -$0.5M to $0.0M | 3 | 2 | 0 |

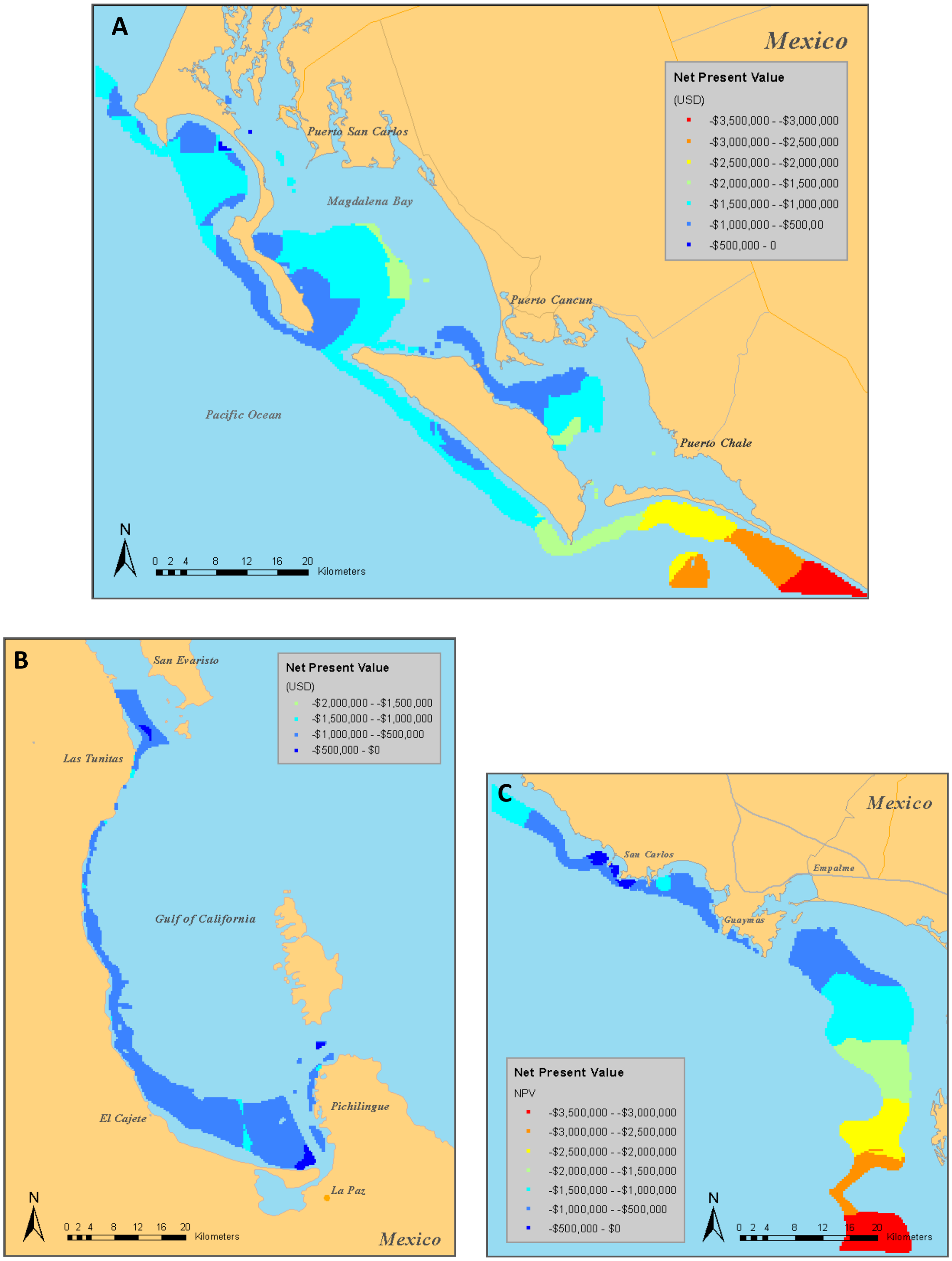



**Figure 22. Standardized ENPVs for the three study areas: (A) Magdalena Bay, (B) Bay of La Paz, and (C) Guaymas Bay.**

## Industrial Model

Modifying production parameters in our spatial bio-economic model, we discovered that expanding Aquapod production to an industrial level creates significant economies of scale, thereby greatly increasing potential profitability. All suitable industrial sites in La Paz are extremely profitable over a 20 year period, as depicted in Figures 23 and 24. The ENPV ranges from 65 to 110 million USD over 20 years. In Figure 24, we see that a majority of sites have ENPVs between $100, and $110 million, with several sites falling tens of millions of dollars below.

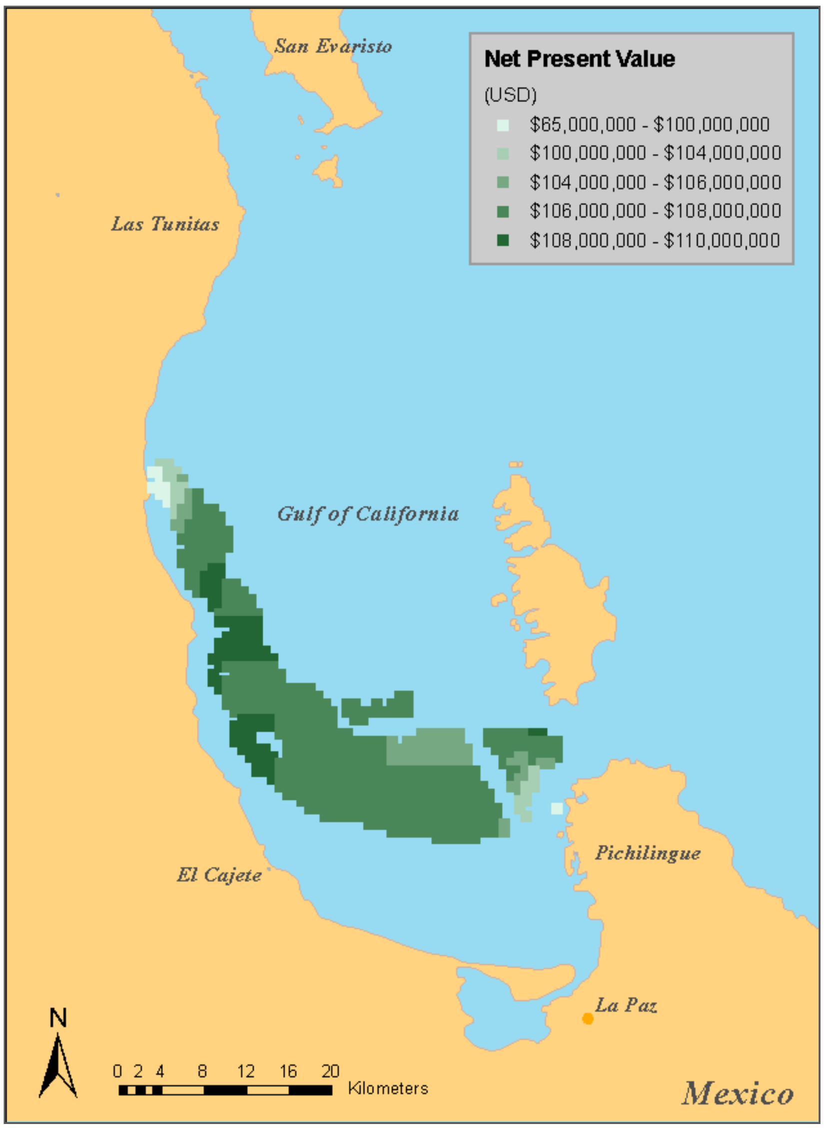



**Figure 23. Map depicting the ENPVs in suitable sites for industrial A-7000 operation in the Bay of La Paz.**

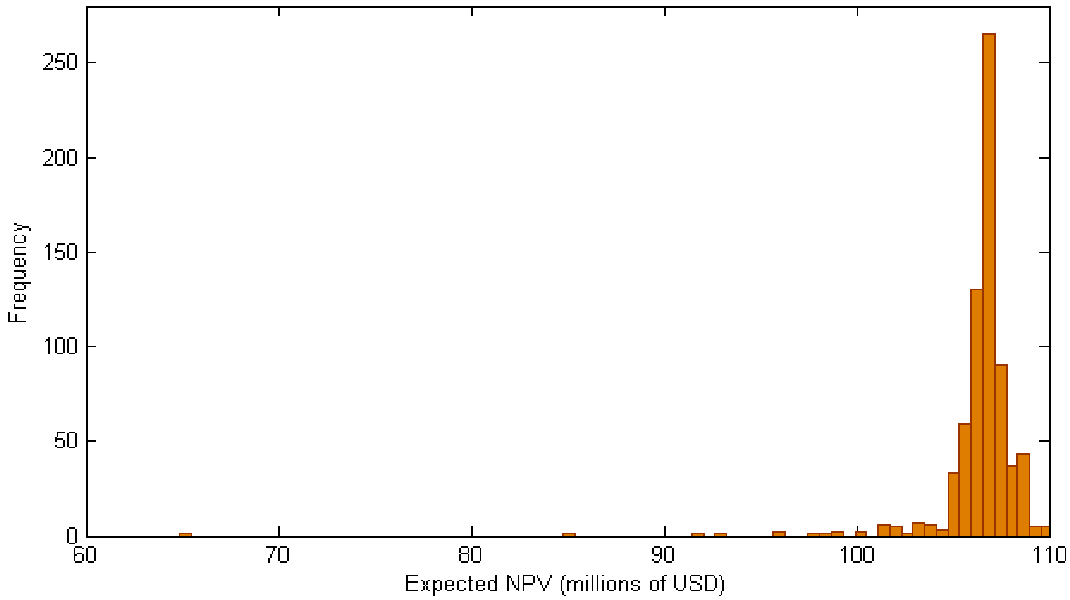



**Figure 24. Histogram depicting the distribution of ENPVs across all sites within La Paz Bay using our industrial model.**

While we know that spatially-linked parameters cause this spatial variation in ENPV, it was difficult to assess which parameters were having the most influence based on the maps and parameter layers alone. We therefore dissected the ENPV calculation and examined spatially-linked parameter outputs individually. We first inspected the site values for spatially-linked parameter outputs in a given year (e.g., the cost of aquaculture risk at every site within the Bay). These spatially linked parameter outputs were revenue, labor costs, travel costs, disease risk costs, pollution risk costs, storm damage risk costs, and ship strike risk costs. We then found the minimum and maximum values within the Bay for each of these spatially-linked parameter outputs in a given year. Finally, we took the difference in these one-year minimum and maximum values (representing the total variation in costs/revenue within the Bay in a given year), and summed that difference over 20 years, with discounting, to generate the variation in NPV within the Bay that could be attributed to each individual cost/revenue. From this examination, we were able to determine which parameter outputs were contributing most to the tens of millions of dollars of variation in the ENPVs across the bay.

**Table 12. Minimum and maximum values for spatially linked parameter outputss in a given year and the total variation in 20 year NPV that can be attributed to each spatially-linked parameter in industrial operation.**

| Spatially Linked Parameter Output | One-year Minimum Value within the Bay (USD) | One-year Maximum Value within the Bay (USD) | 20 year Variation in NPV per Parameter Output (USD) |
|---|---|---|---|
| Disease Risk Costs | $0.02 | $3,422,800.00 | **$44,788,436.00** |
| Revenue | $12,202,800.00 | $12,580,200.00 | **$4,938,400.09** |
| Labor Costs | $474,430.00 | $600,190.00 | **$1,645,609.95** |
| Pollution Risk Costs | $0.03 | $66,928.00 | **$875,774.00** |
| Storm Damage Risk Costs | $4,508.30 | $47,757.00 | **$565,923.12** |
| Travel Costs | $3,774.90 | $41,444.00 | **$492,912.26** |
| Ship Strike Risk Costs | $0.20 | $4,526.00 | **$59,221.55** |

As we can see from Table 12, the main source of ENPV fluctuation is disease risk costs, which are dependent on distance to existing aquaculture and the amount of biomass operators stand to lose to disease mortality. Because the scale at which biomass is being generated in the A-7000 industrial model is extremely large (relative to the scale of the smaller Micropods), operators stand to incur greater losses if disease causes shrimp mortality. This large biomass output, combined with the risk of losing this biomass due to disease from existing aquaculture, accounts for the magnitude of variation we see in ENPV of sites within the Bay of La Paz.

Revenue is the parameter output ranked second in our analysis, but its effects are an order of magnitude smaller than disease risk costs. As a result of our shrimp growth model being dependent on temperature, revenue fluctuates between sites. Minor changes in temperature from site to site can therefore change our biomass output, and thus, our revenue. Again, because the scale at which biomass is being generated in the industrial model is relatively large, minor fluctuations in temperature can result in large changes in revenue.

Our map in Figure 23 is consistent with these results, as the sites of lowest profitability are near sites of existing aquaculture. In contrast to the artisanal model, distance to launch sites appears to have less relative impact on profitability: some of the risk costs outweigh the travel costs due to the larger biomass of the industrial model.

From our analysis, an industrial-scale opportunity may seem attractive to investors, but La Paz may lack the infrastructure needed to support such a large-scale operation. Our analysis does not take into consideration processing and packing facilities, which would be needed in conjunction with a large-scale operation of this type. In the future, on-site research to locate the existing processing facilities and large-scale hatcheries needed to support the industrial model could be integrated into the spatial viability model, strengthening the analysis. A large-scale operation may also face increased resistance from coastal communities, as it is not designed to be operated by the local community. Lack of stakeholder buy-in may be an obstacle in a large-scale operation. By utilizing the suitability map, large-scale operators can begin the process of negotiating with local communities and government entities in order to ensure stakeholder buy-in. It should also be noted that larger pods will have a greater impact on the environment and on-site research measuring the environmental impacts would be extremely valuable.

There were a number of assumptions inherent in this analysis. First, the same growth model and mortality function were applied to the larger A-7000 pods. The density of the pod was the only output-based parameter that was altered based on the size of the pod. In practice, expanding output and applying the same growth and mortality parameters to a much larger pod may be unrealistic. Literature review reveals that this is not necessarily true, due to the drastic variation in surface area to volume ratio between each pod. For instance, in studies done with the culturing of tilapia, researchers have found that higher surface area to volume ratios result in better flushing capacity by water flow (Lim & Webster, 2006). Therefore, since the larger pods have a surface area to volume ratio of 0.25—as opposed to 0.81 of the Micropod—there may be a difference in carrying capacity between Micropods and A-7000s. Overall, our analysis provides a first cut picture of an industrial-scale operation; however, growth scaling considerations and infrastructural challenges must be further evaluated in future modeling of industrial level operation.

## Sensitivity Analyses

Based upon our calculations for each sensitivity analysis, we ranked each parameter in terms of its influence on NPV. The results vary between the elasticity analysis and the parameter value range sensitivity analysis, which highlights the importance of conducting both analyses.

### Elasticity Analysis

The results of our elasticity analysis are essential to informing sound recommendations to our client. When evaluating the list of the top 13 parameters that most influence profit (Table 13), we see that stocking density ranks number one. Stocking density is an extremely important factor, however, the relative ranking here may be misleading given that our shrimp growth and mortality models are not density dependent. In reality, it is likely that high stocking densities will result in increased shrimp mortality, so it would not have an unlimited positive impact on profits.

**Table 13: Results of spatially independent elasticity analysis model parameters.**

| Parameter | Elasticity | Rank |
|---|---|---|
| Stocking density | 18.2 | 1 |
| No. of divers | -16.7 | 2 |
| Dive wage | -15.8 | 3 |
| Feed cost | -9.4 | 4 |
| Panga fuel economy | -5.3 | 5 |
| Maintenance boat fuel economy | -4.9 | 6 |
| Mortality rate | -2.5 | 7 |
| Amount of air | -1.8 | 8 |
| Post-larvae price | -1.5 | 9 |
| Market price bonus | 1.3 | 10 |
| Fixed dive gear cost | -0.8 | 11 |
| Variable dive gear cost | -0.2 | 12 |
| Concession cost | -.01 | 13 |

The parameters ranked second and third on the list—number of divers and dive wage—are interlinked, showing potential for an even larger combined effect of dive time. In our model, these parameters are highly influential, which is not surprising since our business model assumes that these divers work 56 or more hours a week, 355 days a year. It would be difficult for Aquapod operators to reduce the dive wage, as it is partially a function of the local economy and the pay scale required for certified and trained divers. There is potential for Aquapod operators to reduce the number of divers, however, by utilizing different operational business models. For instance, a manager could reduce dive time, and subsequently the number of divers, by installing automatic feeders in each Aquapod. Dive time is also dependent on distance to launch sites, as the divers are paid for their transit time to the Aquapod site. Consequently, another way to reduce dive costs would be to choose an Aquapod site that is closer to a launch site.

Feed cost (ranked fourth) has historically been important for pond aquaculture, and we see the same impact in our offshore aquaculture model. Feed cost depends on two variables: the price of feed and the amount of feed used. The amount of feed used in a harvest cycle can be up to 50,000 kg, which explains why feed cost is so substantial. Our temperature-dependent feed model is based upon historical feeding rates found in pond aquaculture where shrimp are dependent wholly on feed inputs. Field observations of shrimp within the Micropods, however, reveal that the shrimp consume detritus, algae and other natural productivity that accumulate on or inside the pod mesh. Consequently, it is possible that this potential natural nutrient subsidy could reduce the amount of feed required to sustain the shrimp. Potentially, shrimp could even be able to grow by feeding solely off of this natural productivity. As Table 13 indicates, a 1 percent reduction in feed cost will result in a 9.4 percent increase in profitability. An operator could therefore increase profitability significantly by making a just a small decrease in the amount of artificial feed that goes into the Micropod. The operator may also elect to use a less costly feed, such as one derived from fish processing plant waste streams. Feed price, however, typically reflects feed quality, which may affect the growth rate of the shrimp.

The fuel economy (ranked fifth) of each boat significantly influences profit but it is important to note that the elasticity of fuel economy depends upon distance to the nearest launch site. The further the site is from the closest potential launch site, the more impact fuel economy will have on profits. Just for reference, the Bay of La Paz site used to conduct the elasticity analysis is relatively close to shore, as compared to the range of site locations within the Bay. Since the distance to the launch site at this particular location is relatively shorter than the average commute within the Bay of La Paz, this estimation of the elasticity of fuel economy is likely conservative. In general, we would expect fuel economy to affect profitability even more than indicated in Table 13.

## Parameter Value Range Sensitivity Analysis

The parameter value range sensitivity analysis complements our elasticity analysis as it incorporates the varying uncertainty in each parameter, or the relative magnitude of the range of each parameter. When the relationship between the parameter value and NPV is linear, the total profit range's sensitivity depends directly upon parameter range and elasticity. This parameter value range sensitivity analysis is important given that extent of each range varies from parameter to parameter.

**Table 14: The total change in NPVs for the minimum and maximum values for Monte Carlo parameters**

| Parameter | Min Value | Max Value | NPV Result from Min Value | NPV Result from Max Value | Δ NPV | Rank |
|---|---|---|---|---|---|---|
| Stocking density | 200 | 600 | -$1,580,588.79 | $344,515.08 | **$1,925,103.87** | 1 |
| Feed cost | 0.6 | 1.8 | $154,110.18 | -$1,390,178.23 | **$1,544,288.41** | 2 |
| Dive wage | 5 | 12 | $116,327.79 | -$1,352,395.84 | **$1,468,723.62** | 3 |
| No. of divers | 6 | 8 | -$341,219.76 | -$894,848.29 | **$553,628.54** | 4 |
| Mortality rate | 0.001 | 0.01 | -$346,470.74 | -$864,125.02 | **$517,654.29** | 5 |
| Post-larvae price | 0.005 | 0.02 | -$468,233.27 | -$767,834.78 | **$299,601.51** | 6 |
| Amount of air | 12 | 18 | -$562,290.56 | -$673,777.49 | **$111,486.93** | 7 |
| Fixed dive gear cost | 800 | 2000 | -$563,075.68 | -$672,992.37 | **$109,916.70** | 8 |
| Maintenance boat fuel economy | 2 | 4 | -$594,384.07 | -$641,683.98 | **$47,299.91** | 9 |
| Variable dive gear cost | 0.6 | 1 | -$611,530.62 | -$624,537.43 | **$13,006.81** | 10 |
| Ponga fuel economy | 0.4 | 0.8 | -$613,304.03 | -$622,764.02 | **$9,459.98** | 11 |
| Concession cost | 500 | 2000 | -$617,284.02 | -$618,784.02 | **$1,500.00** | 12 |

Table 14 shows the parameters ranked by their influence on profitability (NPV) as determined by the parameter value range sensitivity analysis. Mortality rate ranks much higher in total profit range sensitivity (fifth) than it does in pure elasticity (seventh) because there is an order of magnitude of uncertainty within this parameter's range of values. The wide range in values for mortality is due to the uncertainty inherent in utilizing this new technology. Olazul can reduce this uncertainty in the range of potential mortality rates by investing in equipment that could monitor shrimp mortality within the pod to validate our model. Furthermore, the range of actual observed mortality rates might decrease over several harvest cycles as operators learn more about the operation and improve management practices, thus improving the profitability of the business model.

In contrast to the mortality rate's relative rankings for elasticity and total profit range sensitivity, panga fuel economy drops in rank in the sensitivity analysis due to a relatively small range of parameter values. This means that there is not much difference in our model between a panga near maximum fuel efficiency and a panga near minimum fuel efficiency within the fuel efficiency range. Therefore it is not advisable to devote resources and research time into reducing the uncertainty in the potential range for panga fuel efficiency.

### The Value of Both Sensitivity Analyses

The elasticity and total profit range sensitivity analyses provide complementary insight. Conducting them in combination provides far greater value than one could obtain from doing each analysis individually. Knowing the difference between sensitivity due to profit elasticity versus sensitivity due to parameter ranges will not only provide a more robust analysis, but will also allow us to make more specific recommendations for Olazul's research priorities.

For example, it may be most cost-effective to focus research efforts on reducing uncertainty in the parameters that rank high in total profit range sensitivity and varying management practices to alter the parameters that rank high in the elasticity analysis to increase overall profitability. Achieving shifts or reductions in parameter ranges is not feasible for every parameter (e.g. dive wage), but this general guideline governing elasticity rank versus sensitivity rank provides the most efficient way to improve the viability of Aquapod shrimp aquaculture. By analyzing both elasticity and total profit range sensitivity, we therefore can help our client increase profitability and reduce uncertainty in the most cost-effective way.

## Modeling Alternative Management Scenarios

The flexibility of the spatial bio-economic model allows future users to incorporate new information into the model as it becomes available. The model was designed to be an adaptable tool that can be updated and changed based on user preferences and changing conditions. Alternative management strategies, such as reducing labor or feed costs, could be evaluated using the model to determine how much of an impact that decision would have on the profitability of the Aquapod operation.

In order to demonstrate the value of the tool for informing adaptive management, we modeled NPV under a variety of adaptive management strategies. Our artisanal spatial bio-economic model has demonstrated minimal chances of successful profits over a 20 year period under existing Aquapod management approaches. Despite this setback, opportunities for improvement have been identified through our sensitivity analyses. Strategies to reduce feed and labor costs can greatly increase both the occurrence and degree of profitability within our study sites. Our modeling and analyses have ultimately shown the need for ongoing research and rigorous monitoring through adaptive management. Only through a better understanding of the Aquapod as an integrated biological and economic system can our client, Olazul, achieve the highest chances of success in implementing Aquapod technology as an alternative to unsustainable fishing practices.

### Improving Artisanal Management

Despite the negative profits generated across all sites from our initial spatial bio-economic modeling, an artisanal Aquapod production system holds significant financial potential. As explained in the La Paz NPV discussion section above, 98 percent of the ENPV values across suitable locations in the Bay of La Paz are within a million dollars of being profitable. Over a 20 year period, small management changes could be implemented to drive many, if not all, sites into significantly positive profits.

### Alternative Management Scenarios

Our sensitivity analysis identified multiple parameters that influence profitability. In practice, however, the feasibility of adjusting each parameter varies greatly. Two important parameters that could be readily addressed are feed costs and labor costs.

Feed cost reduction scenarios

A reduction in feed costs can be achieved in multiple ways. One of the promising attributes of Aquapods and their offshore deployment is the potential for shrimp to feed on naturally occurring food sources including algae, zooplankton, and detritus.

Because these sources grow on and are available within the Aquapods, they could greatly reduce the need for artificial feed. Mangers could explore feeding strategies that rely on varying degrees of natural productivity to supplement the artificial feed. Furthermore, modifying daily feeding regiments to match optimal shrimp metabolism can result in higher feed conversion ratios (FCR), resulting in more efficient uptake of applied feed. Future research that compares FCRs for naturally occurring feed to supplemental feed will allow Olazul to better manage feeding protocols. Additionally, feeding strategies could be developed to source artificial feed from waste streams of regional shellfish and bivalve industries. This lower-cost feed source could reduce the amount of the more expensive, conventional feed application, reducing the overall cost of artificial feed. Alternative feeds garner both cost savings and environmental benefits, due to the reduced reliance on processed fish meal and fish oil, which comes from the harvesting of small pelagic fish species integral to the ocean food web. Ultimately, utilizing a combination of these alternative feeding strategies has the potential to greatly reduce feed expenses and increase profitability in the Aquapod production system.

Labor cost reduction scenarios

Our model includes the cost of paying a team of divers to service and maintain the Aquapods, but the efficiency at which this labor is utilized could be greatly improved. In our business-as-usual model, which is based on current management practices, a team of divers travel to the Aquapod site each day, primarily to feed the shrimp. The team also performs routine maintenance on the pods. A majority of the dive time is used by the divers in physically bringing feed to the feed trays within the Aquapods. The daily accrual in shrimp biomass is highly inefficient relative to the current effort divers expend on daily feedings. The development of an automated feeder could greatly reduce this inefficiency. An automated feeder could reduce labor costs by reducing either the amount of diving days or the diving time required to feed the shrimp. As outlined above, Aquapod shrimp may be able to rely on natural productivity as a feed source. In the case of this feed source supplement, divers may be able to deliver less artificial feed to the shrimp, resulting in less diving time, lower labor expenses and higher production efficiency. Regardless of these potential reductions in labor costs, however, divers would still be needed part-time to perform routine maintenance on the pods.

Based on the potential profit increases that could result from reductions in labor and feed costs, we designed five possible alternative management scenarios to evaluate how different combinations of feed and labor cost reductions could improve efficiency and profitability (Table 15). Scenario A represents the “business as usual” management approach. Scenarios B through F capture varying combinations of reductions in feed and labor costs.

Shrimp growth rate reduction scenarios

Altering the amount or type of feed applied may potentially reduce growth rates. Consequently, we also examined how feed and labor reduction strategies would perform under a ten percent reduction in shrimp growth rates in Scenarios G and H (Table 15).

**Table 15: La Paz artisanal management scenarios**

| | 0% Reduction Feed Costs | 50% Reduction Feed Costs | 100% Reduction Feed Costs | | 50% Feed Reduction, 10% Growth Reduction |
|---|---|---|---|---|---|
| **Normal Labor** | Scenario **A** | Scenario **B** | Scenario **C** | | Scenario **G** |
| **Reduced Labor** | Scenario **D** | Scenario **E** | Scenario **F** | | Scenario **H** |

## Modeling Alternative Scenarios

We modeled these seven alternative management scenarios, and evaluated how they influenced profitability across the Bay of La Paz. Labor reduction in our model was represented by one-third of normal effort, equivalent to 104 days of work annually. As previously mentioned, many of the suitable sites in La Paz were negative, but close to reaching profitability over 20 years. Several of the proposed alternative management scenarios were able to bring ALL of the suitable sites into profitability. Table 16 displays the percent of suitable locations that were profitable under each of the management scenarios. Five of the eight scenarios became at least partially profitable including the 50 and 100 percent feed reduction scenarios (B & C), the 100 percent labor reduction scenario (D), and both combinations of feed reduction and labor reduction scenarios (E & F). Histograms depicting the range and distribution of ENPVs across the Bay and of simulated NPV at one particular site (See Appendix F) demonstrate how ENPV range and distributions shift under alternative management practices.

**Table 16. Percentage of suitable sites in the Bay of La Paz with positive ENPVs.**

| | 0% Reduction Feed Costs | 50% Reduction Feed Costs | 100% Reduction Feed Costs | | 50% Feed Reduction, 10% Growth Reduction |
|---|---|---|---|---|---|
| **Normal Labor** | **0%** | **66%** | **100%** | | **0%** |
| **Reduced Labor** | **100%** | **100%** | **100%** | | **100%** |

While the management scenarios improved profitability across the entire bay, spatial variability due to fuel costs and other spatial parameters still impact the amount of profitability at a given site. Figures 25 and 26 depict the spatial variability of profits.



**Figure 25. Map depicting the distribution of ENPVs across all suitable sites within La Paz Bay for scenario C with a 100 percent reduction in feed costs and scenario D (right) with a one-third reduction in labor costs**

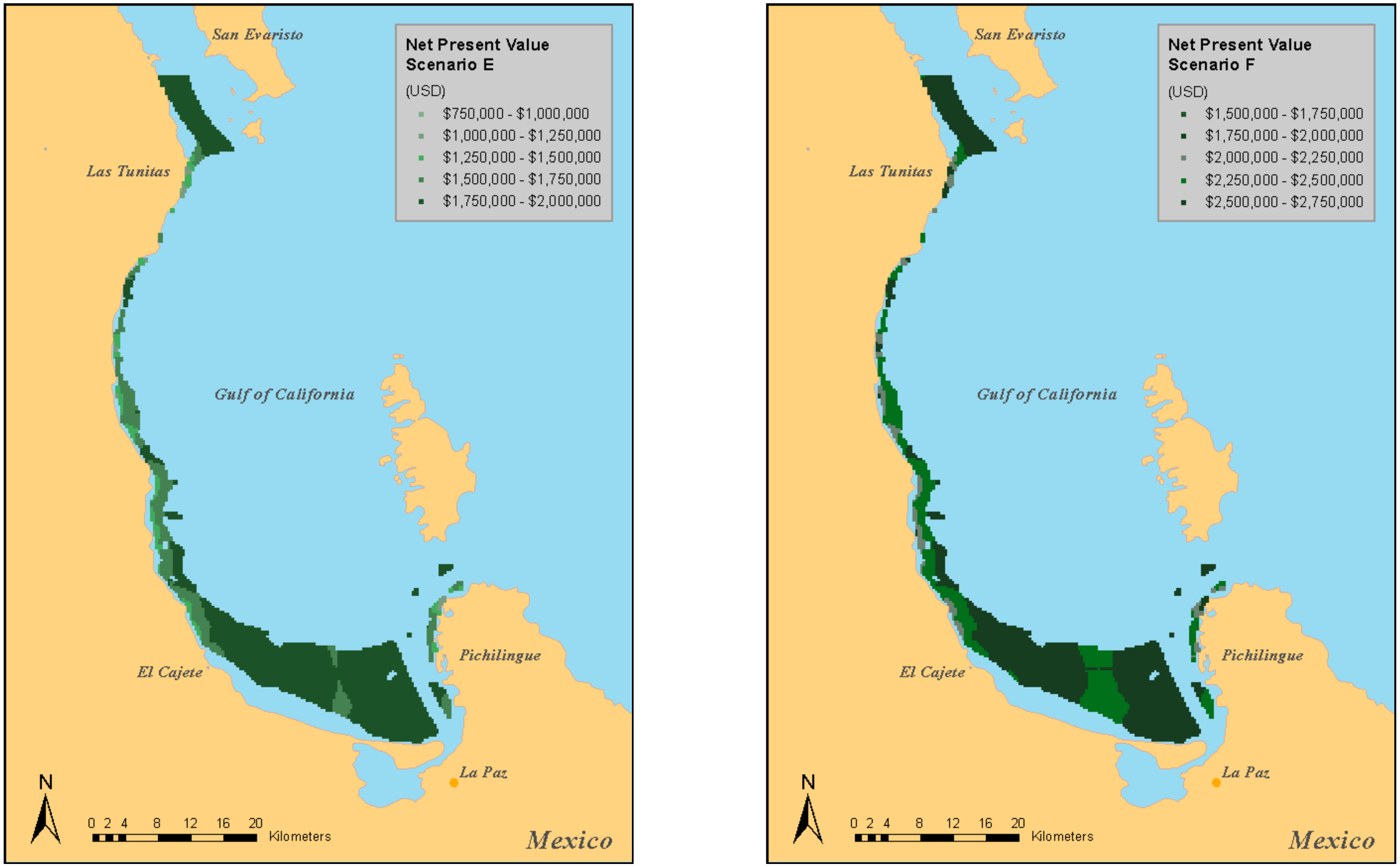



**Figure 26. Map depicting the distribution of ENPVs across all suitable sites within La Paz Bay for scenario E (left) with a one-third reduction in labor costs and a 50 percent reduction in feed costs and scenario F (right) with a one-third reduction in labor costs and zero feed costs in our artisanal model.**

Reducing feed costs by 50 percent (Scenario B) was not enough to bring all suitable sites into profitability, but a majority of sites, 66 percent, did become profitable. In this scenario, we would encourage managers to review the ENPV map (Figure 27) to determine profitable locations. As seen in Figure 28, areas that are furthest from launch sites still display negative NPVs. If alternative launch sites were discovered, profitability margin could shift more toward the positive range, due to the importance of fuel costs in each of these management scenarios.

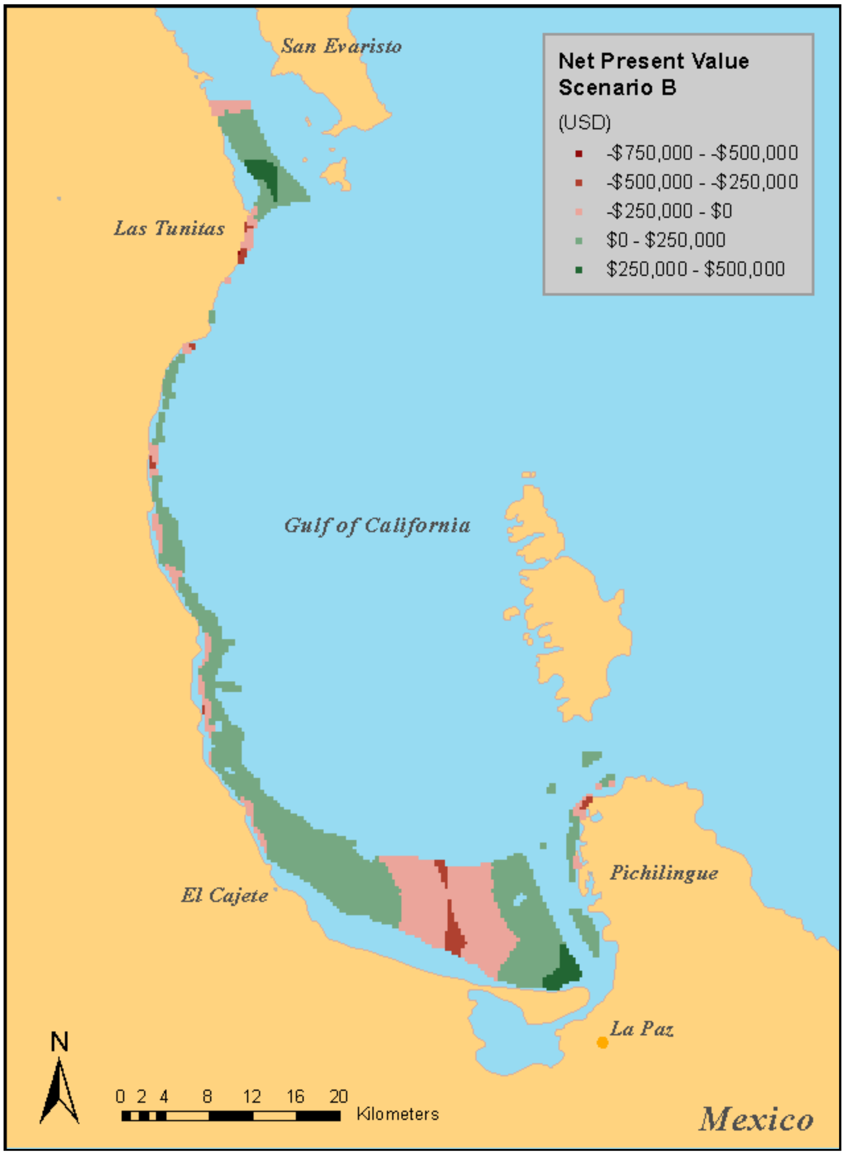



**Figure 27. Map depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz when feed costs are reduced by 50 percent in our artisanal model. Red values indicate regions ranging with no or negative profits and green values indicate profitable regions.**

The range of alternative management scenarios demonstrates the economic potential of the artisanal Aquapod model. The ability to implement each scenario, however, varies greatly. A 100 percent reduction in feed costs (Scenarios C+F) would require a feeding strategy that is entirely reliant on natural feed or no-cost alternative feed sources from byproducts or waste streams. While possible, this 100 percent reduction in feed costs would likely be very difficult to achieve. A more feasible option would be feeding scenarios with a 50 percent feed reduction (Scenarios B+E), which can utilize a combination of conventional, natural, and byproduct feed sources.

Because little is known about how a reduction in feed or use of byproduct feeds will actually affect shrimp growth, it was important to model how a resultant reduction in growth rate could affect the ability of these management scenarios to achieve profitability. We therefore modeled Scenario G, which represents a more realistic option where a 50 percent reduction in feed would decrease the growth rate of shrimp by 10 percent. As Table 16 and Figure 29 illustrate, decreasing the growth rate would lower market price and biomass output, reducing revenue and therefore limiting sites to negative profitability ranges. However, labor costs would also likely be reduced if automatic feeders were installed, or if the number of feeding/dive days was reduced, consequently, we included a reduction in labor in Scenario H. As Table 16 and Figure 28 illustrate, ENPVs could be profitable under the combination of reduced feed costs, reduced growth rates, and reduced labor costs. It is equally important to note that spatial variability of profits occurs under every scenario, therefore managers are encouraged to consult the profitability maps provided.

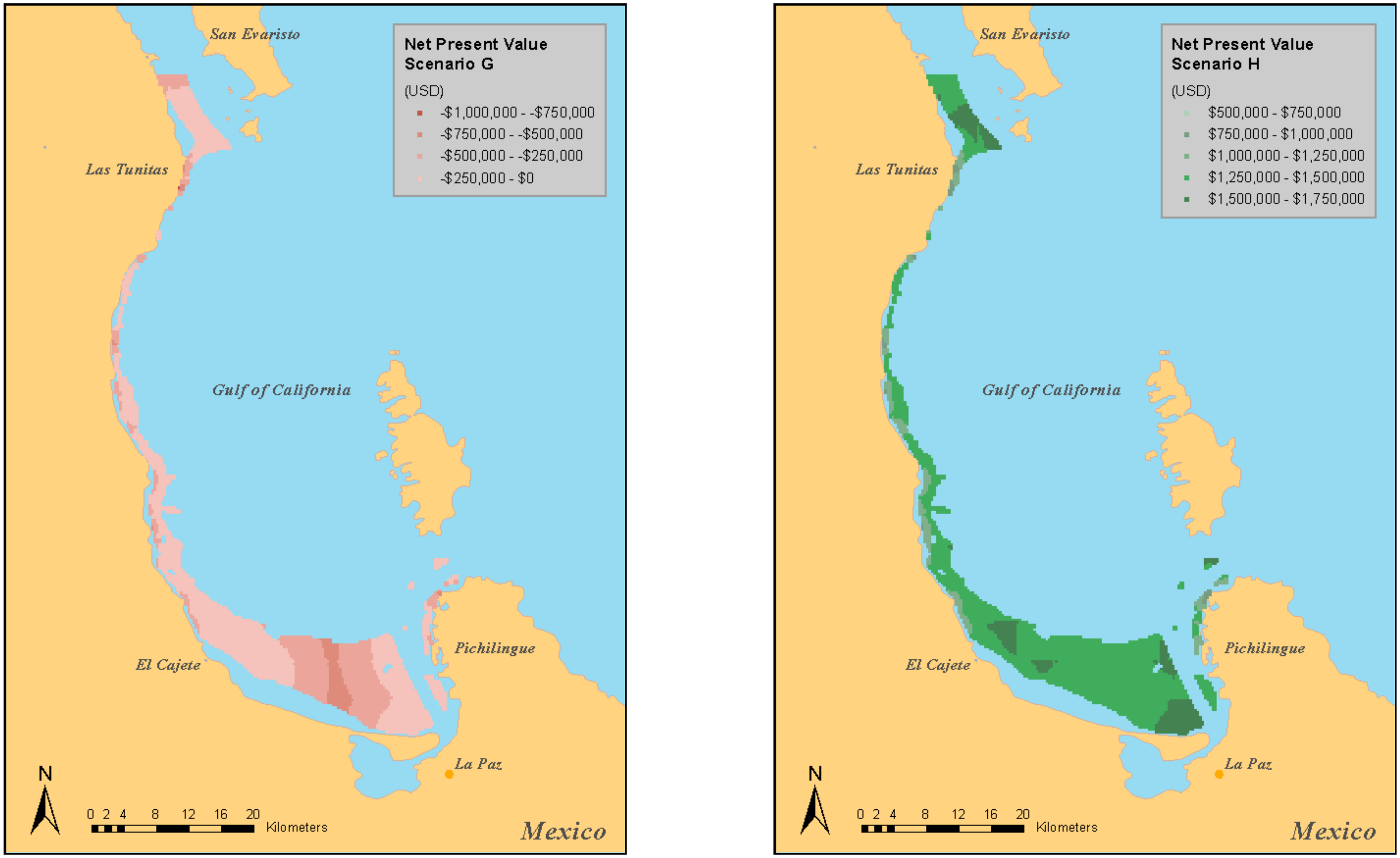



**Figure 28. Map depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz Bay for scenario G (left) where feed costs are reduced by 50 percent and shrimp growth rates are reduced by 10 percent and scenario H (right) where feed costs are reduced by 50 percent, labor costs are reduced by one-third and shrimp growth rates are reduced by 10 percent in our artisanal model.**

Spatial variability in ENPVs

Alternative management decisions can greatly increase ENPVs across the bay, but spatial variability in profits occurs, regardless of the increase profits. Spatial variability in profits can be attributed partially to variance in fuel costs as a function of the distance to launch sites. Other spatial risks, such as distance to shipping lanes (risk of a ship strike) and other aquaculture operations (risk of disease transfer) also play a role in profitability. To demonstrate this spatial variability under alternative management scenarios, we chose two spatially distinct Aquapod deployment sites, as seen in Figure 29. Site 250 is located relatively close to a launch site and relatively far away from pollution sources and other land-based aquaculture farms (both significant sources of risk). Site 3211 is located farther from the nearest launch site as well as far away from pollution outflows and existing aquaculture sites.

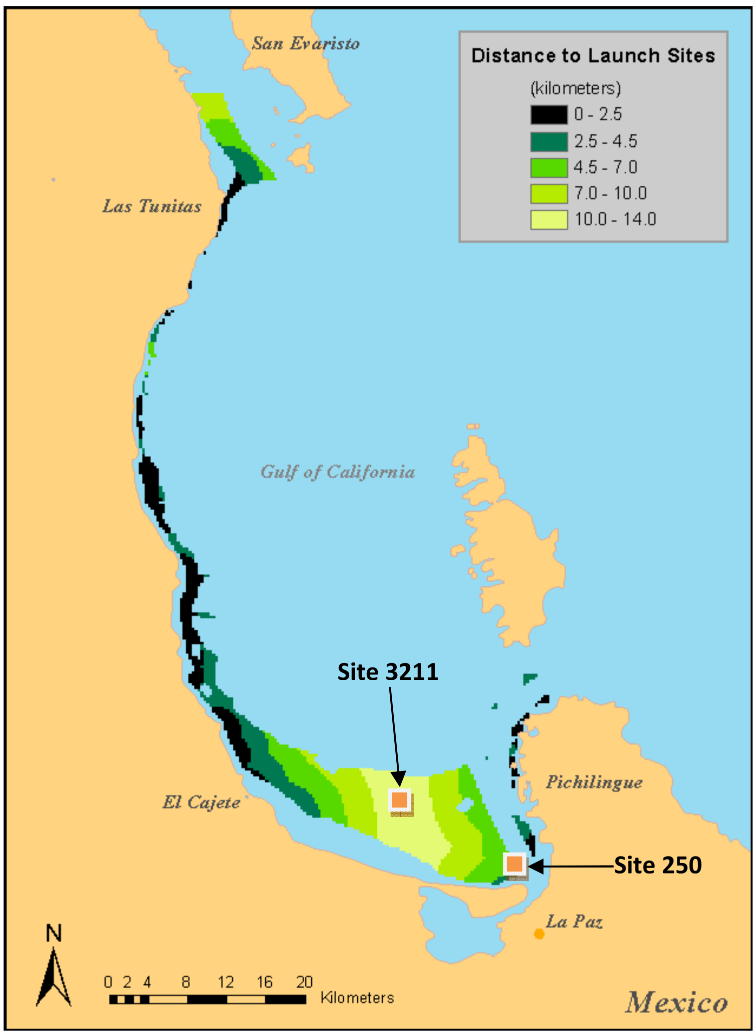



**Figure 29. Map depicting the location of potential Aquapod sites 250 and 3211 and the distance to launch sites within the suitablarea in the Bay of La Paz.**

By comparing the ENPVs from each cell, it is clear that fuel costs as a function of distance to launch sites play a large role in the profitability of Aquapods. All scenarios display greater ENPVs at site 250, while Scenario B and C showed the largest difference, with site 250 exhibiting nearly double the profits of site 3211 (Table 17).

**Table 17. ENPVs of cell 2311 and cell 250 under alternative management scenarios.**

| | NPV Site 2311 | NPV Site 250 | Difference in ENPV (value) | Difference in ENPV (%) |
|---|---|---|---|---|
| Scenario A | **-$1,002,324.36** | **-$499,027.76** | **$503,296.60** | **50.2** |
| Scenario B | **-$259,209.30** | **$261,383.15** | **$520,592.45** | **200.0** |
| Scenario C | **$465,575.69** | **$1,017,492.55** | **$551,916.86** | **118.5** |
| Scenario D | **$983,898.10** | **$1,065,670.01** | **$81,771.91** | **8.3** |
| Scenario E | **$1,748,907.49** | **$1,851,932.49** | **$103,025.00** | **5.9** |
| Scenario F | **$2,471,291.53** | **$2,596,545.94** | **$125,254.41** | **5.1** |
| Scenario G | **-$545,705.52** | **-$15,348.67** | **$530,356.85** | **97.2** |
| Scenario H | **$1,389,951.38** | **$1,501,893.19** | **$111,941.81** | **8.1** |

Informing Management Strategies

Our scenario modeling touches upon the importance of proper planning and improved management to achieve a successful and profitable Aquapod operation. As we saw within the Bay of La Paz, profitability varied greatly under different management scenarios, and between each location. Therefore, managers will need to consider both best management practices and spatial parameters to achieve successful Aquapod implementation. Our approach is valuable to future Aquapod managers, as we have identified which parameters influence profitability the most in our sensitivity analysis. From there, managers can decide which research priorities and management scenarios are most feasible. For example, reducing feed and labor costs may be more practical than finding an alternative launch site closer to the Aquapod deployment site. By utilizing our spatial bio-economic model and framework for analysis, managers will be able to identify management options that work for them, and then develop an Aquapod implementation strategy that best suits their needs.

## Evaluating Competing Uses

While this modeled profitability of Aquapod operations under various management strategies is informative, in reality, this use would have to compete for space and resources with other uses within the bays. One such competing use that could be disturbed by Aquapod implementation is fishing, both commercial and artisanal. The Gulf of California is rich in biological diversity and has high rates of primary production due largely to the Gulf's temperate latitude, complex topography, and the presence of seasonal, nutrient-rich upwelling zones (Ulloa et al., 2006). Because of its rich biological diversity and high rates of primary production, many areas of the Gulf are important fishing zones. The total value of fisheries within the Gulf region is estimated to exceed 300 million USD (500,000 tons) per year, accounting for 70 percent of Mexico's annual fisheries revenues (50 percent of total volume) (Ulloa et al., 2006). Gulf fisheries, including primarily anchovy, sardine, tuna, shrimp and squid, supply nearly 250 processing plants and generate over 50,000 jobs (Ulloa et al., 2006). As of 2002, over 30,000 fishing vessels were registered in the region, including 1,674 shrimp boats and 28,700 coastal fishing vessels (pangas) (SourceMex, 2010; Ulloa et al., 2006). Ports in the Gulf house nearly 100 percent of the nation's anchovy and sardine vessels, 72 percent of its tuna vessels, and 55 percent of its shrimp boats (Ulloa et al., 2006). Consequently, local fishers might be opposed to closing off areas to fishing or trawling so that Aquapods can be installed.

For example, within the Bay of La Paz, multiple fisheries—including cartilaginous fish, mollusks and squid—currently generate socioeconomic value to local coastal communities. Our spatial bio-economic analysis provides a means for examining which activities potentially generate more economic value within a spatial context. Figure 30 depicts a map of the total annual fisheries value within the Bay of La Paz, compiled from fishing effort maps and CONAPESCA landings data. [8] We see that the fishing sites within the area suitable for Micropods currently generate between 57,000 and 187,000 pesos per site per year (approximately 4,700 to 15,600 USD[9]). As a rough estimate (not including a discount rate), we can calculate that if fishing profits for all fished species in the area continued at this rate in the future (a generous assumption, given the declining state of most fisheries today), these sites would generate between 94,000 and 3,740,000 USD over a 20 year period.

---

[8] This analysis was completed by one of our team members and her classmates for a conservation planning class at Bren. Data was provided by COBI and TNC. The group is currently pursuing publication of this study, and has provided us with permission to use this unpublished figure in the meantime (A. Tresham, C. Sanneman, K. Labrum, and A.R. Callahan; personal communication; March 1, 2011).

[9] Pesos converted to USD using OANDA (http://www.oanda.com/currency/converter/) exchange rates on March 15, 2011.

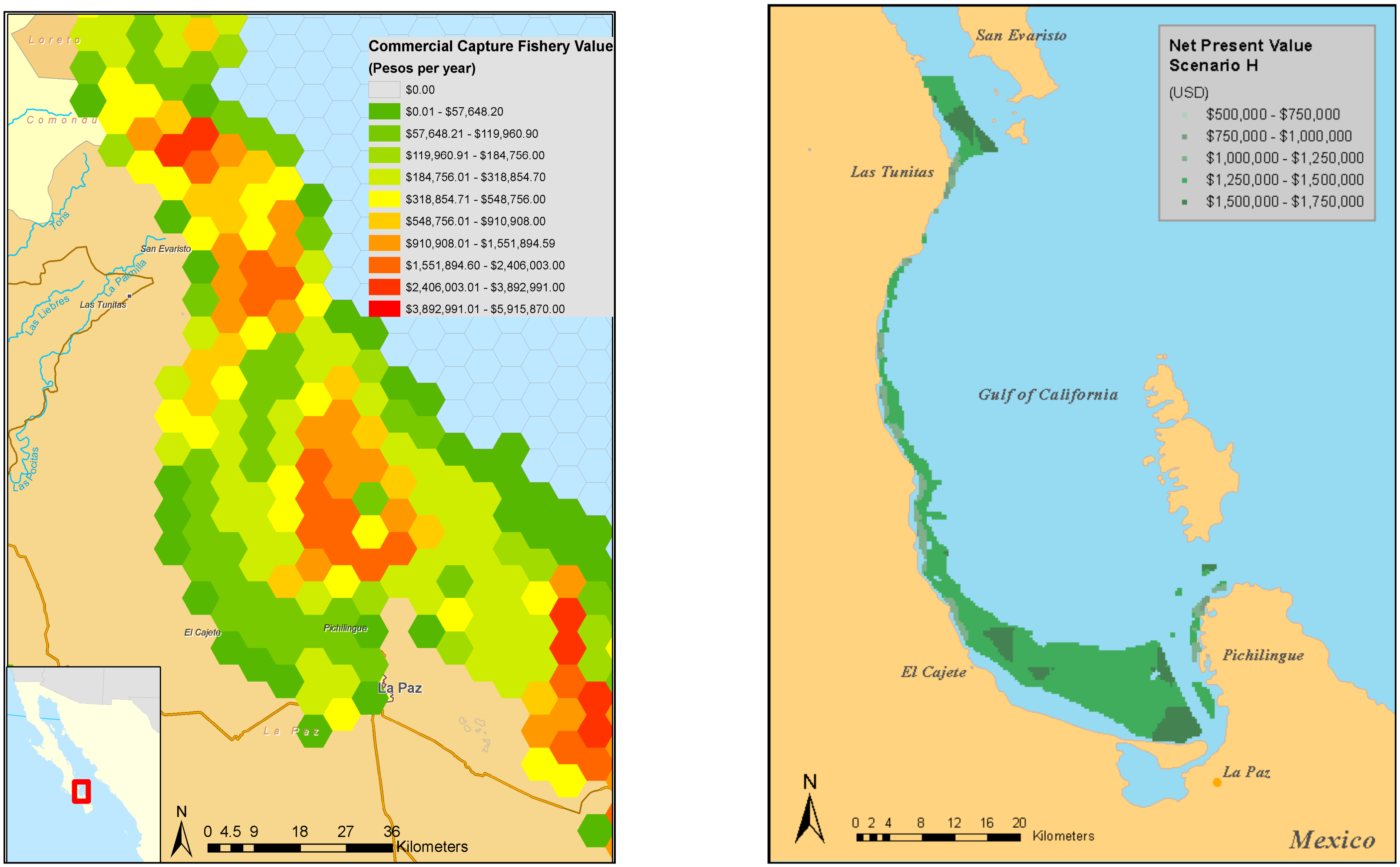



**Figure 30. Map depicting the total annual capture fishery value in the Bay of La Paz (left); Map depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz Bay for scenario H (right), where feed costs are reduced by 50 percent, labor costs are reduced by one-third and shrimp growth rates are reduced by 10 percent in our artisanal model.**

Comparatively, the artisanal Micropod model under one of our more realistic scenarios, scenario H (reduced feed costs, reduced growth rates, reduced labor costs), would generate between 600,000 and 1,550,000 USD over 20 years. Clearly, the artisanal Micropod model is an economically viable alternative to fishing in some of these areas. Furthermore, we see from Figure 30 that the areas suitable for Micropod siting do not overlap areas of highest fishing value.

This brief comparison of the economic value of fisheries with the potential economic value of Aquapod shrimp farming shows the potential of our spatial bio-economic framework as an outreach, communication and planning tool. The spatial maps of fishing profit and Aquapod profit could be used to communicate to local community members about the advantages of Aquapod operations or to discuss potential Aquapod siting plans that would minimize impacts to local fisheries.

## Recommendations to Olazul

After researching both the site-suitability and the economic profitability of Aquapods in Northwestern Mexico, we recommend the following to Olazul to increase the likelihood of successful integration of Aquapod technology into existing communities:

**1. Focus research efforts on the Bay of La Paz study area**

Based on the spatial bio-economic analysis of the three study areas, La Paz has the most potential for successful and profitable Aquapod operations. While La Paz does exhibit negative profits under the "business as usual" scenario, many of the sites require only small changes in management strategies (relative to Guaymas and Magdalena Bay) to shift profits into the positive range. Furthermore, valuable stakeholder connections have already been cultivated in La Paz, which will further increase the chance of project success. While the fishing heritage of Guaymas Bay and the depressed economy and superior environmental conditions in Magdalena Bay would suggest that these areas are prime locations for Aquapod placement, the large range of negative profits in these bays would make it difficult for investors and communities to sign on to an Aquapod project.

**2. Conduct on-site research to increase probability of successful placement**

Suitable sites for Aquapod placement have been determined by utilizing existing large-scale spatial data. It is recommended that Olazul collect in-situ temperature data to parameterize the site suitability model to more accurately reflect on-site environmental conditions:

- ***Sea surface temperature*** – installing temperature probes at the sea surface will enable comparison with the large-scale SST satellite data.
- ***Temperature at depth*** – Installing probes at the top and bottom of the Aquapod can help inform the difference in temperature at depth from the surface and how much it fluctuates at depth. This information can later be used to parameterize SST satellite data at future deployment sites.

**3. Investigate environmental impacts of Aquapods**

Offshore submerged caged aquaculture is believed to have reduced environmental impacts due to the increased ocean currents and deeper waters which readily flush effluents and toxins. Determining the environmental impact of Aquapods could greatly enhance the marketability of Aquapod products, as well as assist in future legislation regarding offshore aquaculture. The following studies should be pursued to evaluate environmental impact:

- ***Establish water quality baselines*** – installing probes for dissolved oxygen, ammonia, and pH inside, adjacent to and below the Aquapods will assist in establishing management protocols as well as in determining the environmental impact of Aquapods.

- ***Measure oceanographic currents*** – determining the speed and direction of the currents will assist with risk assessment protocols. Currently many of the risks are based on "first principles" of diffusion. Increased understanding of actual currents will help determine how the Aquapods may interact with each other (e.g., disease transfer, nutrient flow, etc.) as well help determine the environmental impact and vulnerability of the pods to risks from pollution and land-based aquaculture disease sources.
- ***Monitor effluent*** – Offshore aquaculture is *believed* to have reduced environmental impacts based on reduced sedimentation of effluent due to increased ocean currents. By placing sampling containers directly under the Aquapods as well as on the benthos, a better determination can be made as to whether the validity of the hypothesis that offshore currents diffuse harmful effluent.

**4. Develop a greater understanding of competing uses and risks**

Working with local non-profit organizations, such as Noroeste Sustentable, the suitability maps can be used in public meetings to gain a better understanding of how suitable locations of Aquapod deployment may interact or conflict with existing uses and what other risks may pose a threat to Aquapod operations. Much of the social data needed to fully address the "competing use" question can only be gained through on-the-ground communication and outreach efforts. Future beneficial socio-economic data could include:

- ***Locations of existing fishing communities*** which would benefit from community ownership of Aquapods.
- ***Locations of established fishing grounds*** which would directly compete with Aquapod placement.
- ***Survey of current uses***, such as recreational boat traffic, dive locations, etc. in the suitable areas that may conflict with or pose a threat to Aquapod operations.

**5. Research the feasibility of suggested management scenarios**

As mentioned in the discussion sections above, alternative management decisions may increase the probability of successful Aquapod implementation. These management scenarios offer insight into future management decisions and assist managers in prioritizing research needs. Some of the management scenarios will be easier to implement than others and we recommend Olazul consider each scenario and then utilize contacts in Mexico to gain a better understanding of the feasibility of each scenario.

**6. Research additional beach access points for Aquapod operation deployment**

Due to the daily maintenance required for Aquapod production, deploying Aquapods close to launch sites is highly recommended. Fuel costs are spatially correlated and play a large role in the profitability of Aquapod operations. Daily fuel costs can be reduced by locating pods close to shoreline launch sites, allowing for greater flexibility in feed and labor expenditures. For the purposes of this study, beach launch sites were defined as beaches with road access. In order to increase overall profitability it may be cost effective to research additional useable launch sites through on-the-ground community research. Once an optimal launch site is determined, the spatial bio-economic analysis can be individually tailored, adjusting the overall expected net present value.

## Conclusions

Olazul asked our project team to develop a comprehensive framework to inform the planning, development and future research priorities for Olazul's Aquapod operations within three study regions in Northwestern Mexico: The Bay of La Paz, Magdalena Bay and Guaymas Bay. Our deliverables to Olazul include a site-suitability tool for assessing potential Aquapod siting within each region, as well as maps of the suitable and profitable zones in our three study areas, an intra- and inter-site profitability analysis, and a sensitivity analysis indicating which parameters most influence Aquapod profitability. This set of modeling and planning tools will assist our client in establishing successful Aquapod operations and ultimately help transition local communities from a dependency on destructive aquaculture and capture fisheries to a model of economic and environmental sustainability. By utilizing the new planning tools and adopting an adaptive management approach, Olazul can effectively lower both environmental and economic costs.

Our initial business model, which was derived from existing shrimp Aquapod aquaculture operations, proved to be unprofitable, ultimately highlighting inefficiencies in the current management practices. Our maps illustrate that spatially-dependent economic costs, such as fuel and labor costs, also played a large role in the profitability of Aquapod operations. Initial negative returns prompted us to explore alternative management scenarios that change the parameters that most influence profit, such as altering the amount of feed and the number of divers used. Therefore, by reducing feed and labor costs through the various scenarios mentioned above, and utilizing the site-suitability map to research suitable locations close to launch sites, Aquapod operators have a much higher chance of securing positive profits. Individual operators of Aquapods could utilize our spatial bio-economic planning tool to input their own management plan and determine strategies for the highest chances of successful operations.

### Application of Our Analysis

#### Reducing economic and environmental costs

Trial and error implementation of a new technology can be economically and environmentally costly. As seafood operations mature, they work through their economic inefficiencies and reduce their negative environmental impacts, ultimately producing more seafood and reducing impacts to the environment. It is therefore environmentally and economically beneficial to bypass the trial and error stage, and start production at an efficient level. Our spatial bio-economic analysis provides a cost-efficient method for addressing the uncertainty inherent in offshore aquaculture production. Management practices, such as feed ratios and dive time, can be economically assessed and tailored for individual operations to test which inputs impact production the most. Our spatial bio-economic framework allows operators to reduce costs through reducing uncertainty and replacing the trial and error approach with well-informed management plans.

### Integrating social and environmental concerns

Concurrent research is assessing the environmental impacts of offshore aquaculture and how it can be integrated into communities and moved in a more sustainable direction. Our research complements these efforts and provides a framework to integrate social, environmental and economic considerations into developing offshore shrimp aquaculture. Our analysis provides a foundation with which to assess future environmental and socio-economic impacts, which ultimately will help provide maximum new benefits without compromising other uses. Once environmental impact data becomes available for Aquapods, it can be incorporated into our analysis to provide information regarding the environmental and economic optimal locations. For example, if new research shows that Aquapods should be spaced further apart due to risk of disease transfer, this can easily be adapted in the GIS model by increasing the cell size of our analysis. If Aquapods need to be placed in faster currents or deeper waters due to effluent concerns, these can all be easily integrated into our spatial bio-economic analysis.

Furthermore, determining regions that are suitable for Aquapod implementation can help reduce conflict in the public planning and policy process. Stakeholders have the opportunity to voice concerns through discussions of current competing uses, as well as non-established, but culturally important, competing uses that are within the suitable locations displayed on the site-suitability map. These maps can be used to launch dialogues between stakeholder groups, ultimately reducing user conflicts and increasing policymakers' understanding of the current and future uses of a particular area.

## Value in our Approach

As the global demand for seafood increases, so does the need for alternative methods of seafood production. In 2010 aquaculture production reached an all-time high accounting for over half of the seafood production in the world. As the availability of coastal land for land-based aquaculture becomes scarce, people are beginning to look offshore in order to meet these demands. While moving operations offshore may mitigate some of the negative environmental impacts of aquaculture, it places aquaculture in direct competition with current offshore uses, such as fishing grounds and shipping routes, as well as future uses, such as offshore energy development and marine reserves. Marine spatial planning is currently being used to address some of these spatial concerns by working with stakeholders to map their current and future uses. This effort is a critical component for successful planning, yet we believe having a way to evaluate an offshore location based on its economic performance allows for even greater understanding and flexibility in the planning process. The spatial bio-economic tools and framework we have created can be used to assess various offshore activities by assigning a location an economic value, which can then easily be compared with other locations, as well as other uses. This quantitative method of analysis provides a starting point for future discussions with stakeholders in which social values and environmental concerns can be also addressed.

## Works Cited

Administracion Portuaria Integral. ( n.d.). Port of Pichilingue - Mexico - Port Information. Retrieved from http://www.bestmaritimeemployment.info/ catalogue_companies_list/company_source_29074_1.html

Aguado-Gimnez, F. & Garca-Garca, B. (2004). Assessment of some chemical parameters in marine sediments exposed to offshore cage fish farming influence: a pilot study. *Aquaculture, 242*(1-4), 283-295.

Alston, D., Cabarcas, A., Capella, J., Benetti, D., Keene-Meltzoff, S., Bonilla, J., and Cortés, R. (2005). *Environmental and Social Impact of Sustainable Offshore Cage Culture Production in Puerto Rican Waters*. (NOAA Federal Contract Number: NA16RG1611.)

Benetti, D., Brand, L., Collins, J., Orhun, R., Benetti, A., O'Hanlon, B., . . . Cabarcas, A. (2006). Can offshore aquaculture of carnivorous fish be sustainable?: Case studies from the Caribbean. *World Aquaculture, 37*, 44-47.

Benetti, D. D., Orhun, M. R., Zink, I. C., Cavalin, F. G., Sardenberg, B., Palmer, K., . . . O'Hanlon, B. C. (2007). Aquaculture of Cobia (*Rachycentron canadum*) in the Americas and the Caribbean. In I.C. Liao & E.M. Leano (Eds.), *Cobia Aquaculture: Research Development and Commercial Production* (57-77). Manila, Philippines: Asian Fisheries Society.

Balogun, Adbesisi M., Samsons, Yemi. (1992). Waste yield, proximate and mineral composition of shrimp resources of Nigeria's Coastal Waters. *Bioresource Technology, 40,* 157-161

Cacho, O. J. (1997). Systems modelling and bioeconomic modelling in aquaculture. *Aquaculture Economics & Management*, *1*(1), 45–64.

Cembali, T., Folwell, R. J., Huffaker, R. G., McCluskey, J. J., & Wandschneider, P. R. (2007). Economics of alternative simulated manual asparagus harvesting strategies. *Agricultural Systems*, *92*(1-3), 266–294.

CIBNOR (n.d.). Homepage. Retrieved from http://www.cibnor.mx/.

CONAPESCA. (2007). *Anuario Estadistico de Acuacultura y Pesca: Anuario 2007*: *Comisión Nacional de Acuacultura y Pesca*.

Cruz-Torres, M. L. (2000). Pink gold rush: Shrimp aquaculture, sustainable development and the environment in northwestern Mexico. *Journal of Political Ecology: Case Studies in History and Society*, *7*(1), 63-90.

Dubay, K., Tokuoka, S., & Gereffi, G. (2010). *A value chain analysis of the Sinaloa, Mexico Shrimp Fishery*. Retrieved from Duke University - Center of Globalization and Governance and Competitiveness (CGGC) website: http://cggc.duke.edu/.

Ehler, C., and F. Douvere. (2009). Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. *Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. Paris: UNESCO.* 99 pp.

EPRI. (2006). Remotely operated vehicle (ROV) technology: applications and advancements at hydro facilities. Electric Power Research Institute.

*Explorando Mexico*. (2010). Illegal commerical fishing in Mexico." Retrieved from http://www.explorandomexico.com/about-mexico/8/363/.

Gillett, R D. (2008). Global study of shrimp fisheries. FAO Fisheries Technical Paper. Retrieved from http://www.fao.org/docrep/011/i0300e/i0300e00.HTM.

Hernadez, A., & Kempton, W. (2003). Changes in fisheries management in Mexico: Effects of increasing scientific input and public participation. *Ocean & Coastal Management,46*(6), 507-526. doi: 10.1016/S0964-5691(03)00032-2.

Hernandez-Llamas, A., Gonzalez-Becerril, A., Hernandez-Vazquez, S., & Escutia-Zuñiga, S. (2004). Bioeconomic analysis of intensive production of the blue shrimp *Litopenaeus stylirostris* (Stimpson). *Aquaculture Research*, *35*(2), 103-111.

INAFED. (2010). Estado De Sonora. *Instituto Nacional Para El Federalismo Y El Desarrollo Municipal*. Retrieved from http://www.elocal.gob.mx/wb2/ELOCAL/EMM_sonora/.

Kam, L. E., Leung, P. S., & Ostrowski, A. C. (2003). Economics of offshore aquaculture of Pacific threadfin (Polydactylus sexfilis) in Hawaii. *Aquaculture*, *223*(1-4), 63–87.

Kazmierczak, R. F., & Caffey, R. H. (1995). Management ability and the economics of recirculating aquaculture production systems. *Marine Resource Economics*, *10*(2), 187–209.

Lim, C., Webster, C. (2006). Tilapia: Biology, Culture, and Nutrition. Binghamton, New York: The Haworth Press, Inc.

Mahdi, A., Robertson, A. (Producers), & Mahdi A., Robertson A. (Directors). (Novemeber 16, 2010). *Aquapods: the search for sustainable shrimp* [Documentary] (Available from Olazul, 2420 Sand hill Road, Menlo Park, CA 94025).

Meyer, F. P. (1991). Aquaculture disease and health management. *Journal of animal science*, *69*(10), 4201.

NOAA National Marine Fisheries Service, Office of Protected Resources. (n.d.). Turtle excluder devices (TEDs). Retrieved from: http://www.nmfs.noaa.gov/pr/ species/turtles/teds.htm.

NOAA National Marine Fisheries Service, Office of Science & Technology (NMFS). (2009). *Fisheries of the United States-2008*. Retrieved from http://www.st.nmfs.noaa.gov/ st1/fus/fus08/index.html.

Ocean Farm Technologies, Inc., (OFT). (n.d.). *Aquapod Net Pens*. Retrieved from http://www.oceanfarmtech.com/aquapod.htm.

Páez-Osuna, F. (2001). The environmental impact of shrimp aquaculture: causes, effects, and mitigating alternatives. *Environmental Management, 28*(1), 131–140.

Páez-Osuna, F., Garcia, A., Flores-Verdugo, F., Lyle-Fritch, L. P., Alonso-Rodríguez, R., Roque, A., & Ruiz-Fernández, A. C. (2003). Shrimp aquaculture development and the environment in the Gulf of California ecoregion. *Marine Pollution Bulletin, 46*(7), 806-815.

Page, S. (2005). *Ocean Farm Technologies, Inc. Presentation: Fish Farming in the Open Seas*. [PowerPoint slides]. Retrieved from http://www.oceanfarmtech.com/downloads/ presentation_fish_farming.pdf.

Pickell, J. (2009). BCS launches citizen vigilance program to limit illegal fishing. *CalyCanto*. Retrieved from http://www.calycanto.com/press/illegal-fishing-baja.

Piszcz, D. (2006). Local firm receives Maine technology institute award. *Belfast Republican Journal*.

Ray, G. C. (2010). Coastal and marine spatial planning: a policy waiting to happen. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *20*(4), 363-364.

Roberts, J.J., B.D. Best, D.C. Dunn, E.A. Treml, and P.N. Halpin. (2010). Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. *Environmental Modeling & Software, 25*, 1197-1207.

Smith, Bain. (2004, October). Sea Watch, Magdalena Bay, B.C.S. *Seawatch*,. Retrieved from http://www.seawatch.org/newsroom/.

Snapperfarm, Inc. (2007). About Ocean Ocean Aquaculture. *Snapperfarm Open Ocean Aquaculture*. Retrieved from http://www.snapperfarm.com/2006/aboutopenoceanaquaculture.htm.

SourceMex. (2010, March 10). U.S. imposes embargo on some imports of Mexican shrimp. The Free Library. Retrieved from http://www.thefreelibrary.com/U.S. IMPOSES EMBARGO ON SOME IMPORTS OF MEXICAN SHRIMP.-a0220864624.

Stanford, S. (2010, May 10). Information on La Paz, Baja California. *EHow*. http://www.ehow.com/about_6500078_information-la-paz_-baja-california.html.

TheFishSite (2008, April). US Shrimp Market Report. Retrieved from http://www.thefishsite.com/articles/431/us-shrimp-market-report-april-2008

Ulloa, R., Torre, J., Bourillón, L., Gondor, A. & Alcantar, N. (2006). Ecoregional planning for marine conservation, Gulf of California and west coast of Baja Southern California. Final report to The Nature Conservancy. Guaymas, Sonora Community and Biodiversity, AC, 153 pp.

Umesh, N. R., Mohan, C. V., Phillips, M. J., Bhat, B. V., Babu, G. R., Mohan, A. B., & Padiyar, P. A. (2008). Risk analysis in aquaculture–experiences from small-scale shrimp farmers of India. *Understanding and applying risk analysis in aquaculture*, 247.

University of New Hampshire (UNH). (2007). *Finfish Aquaculture Cages* in UNH Atlantic Marine Aquaculture Center: Offshore Submerged Finfish Culture. Retrieved from http://ooa.unh.edu/finfish/finfish_cages.html.

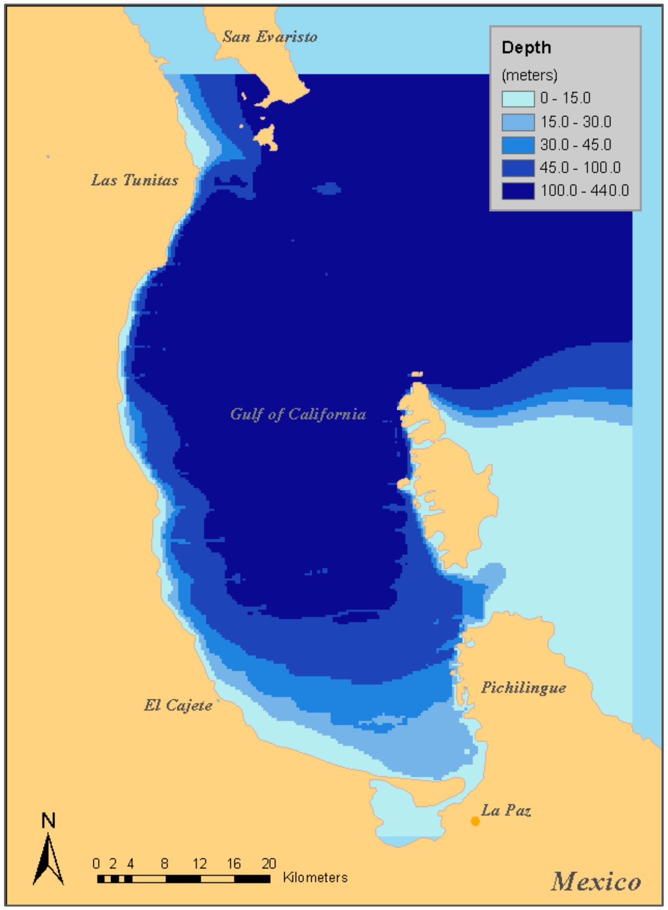
Wang, David W., Mitchell D. A., Teague, W. J., Jarosz, E., & Hulbert, M. S. (2005). Extreme waves under hurricane Ivan. *Science* 309.5736: 896 Retrieved from http://www.sciencemag.org/content/309/5736/896.full.

Wyban, J., Walsh, W. A., & Godin, D. M. (1995). Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp (Penaeus vannamei). *Aquaculture*, *138*(1-4), 267–279.

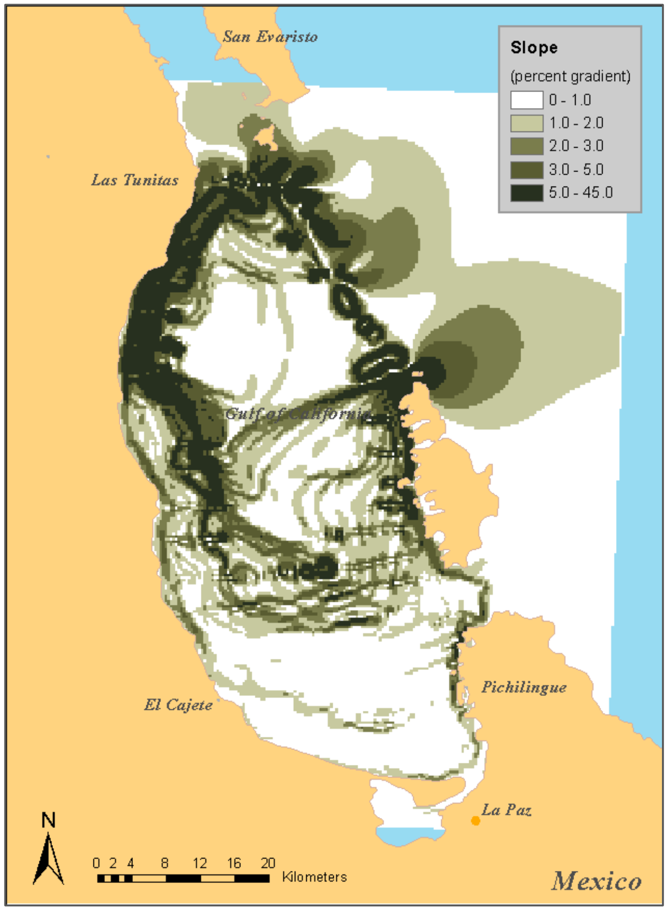
# Appendix

## A. Maps of Spatial Data Inputs for GIS Site-Suitability Model

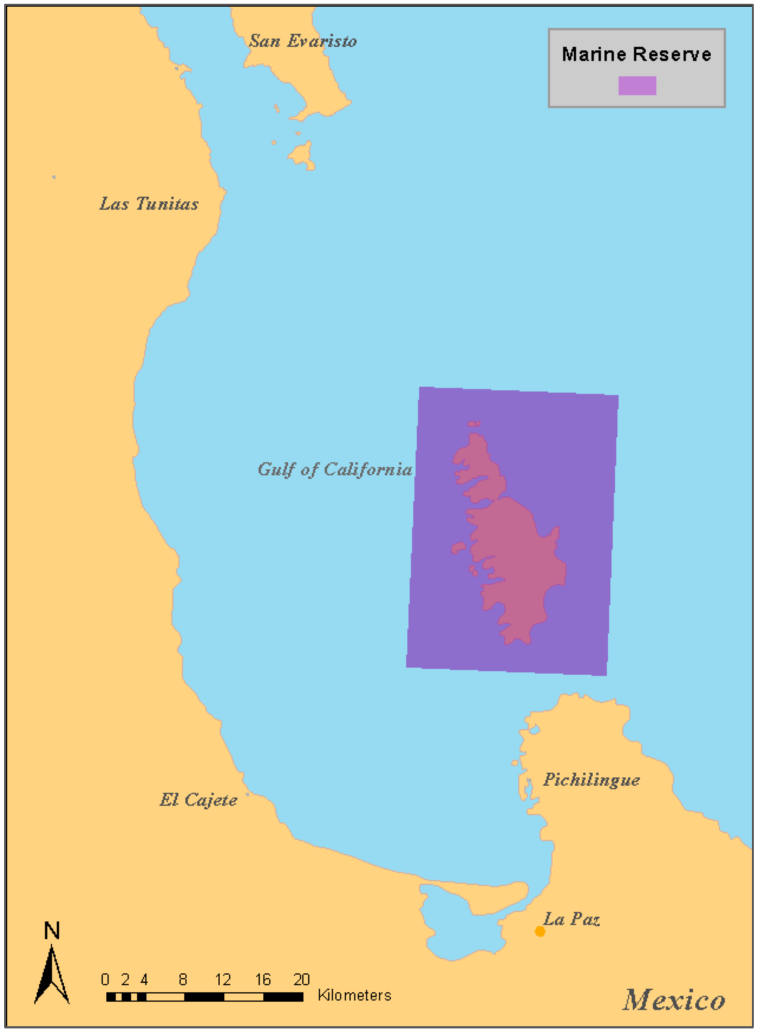
Appendix A1. Depth– La Paz



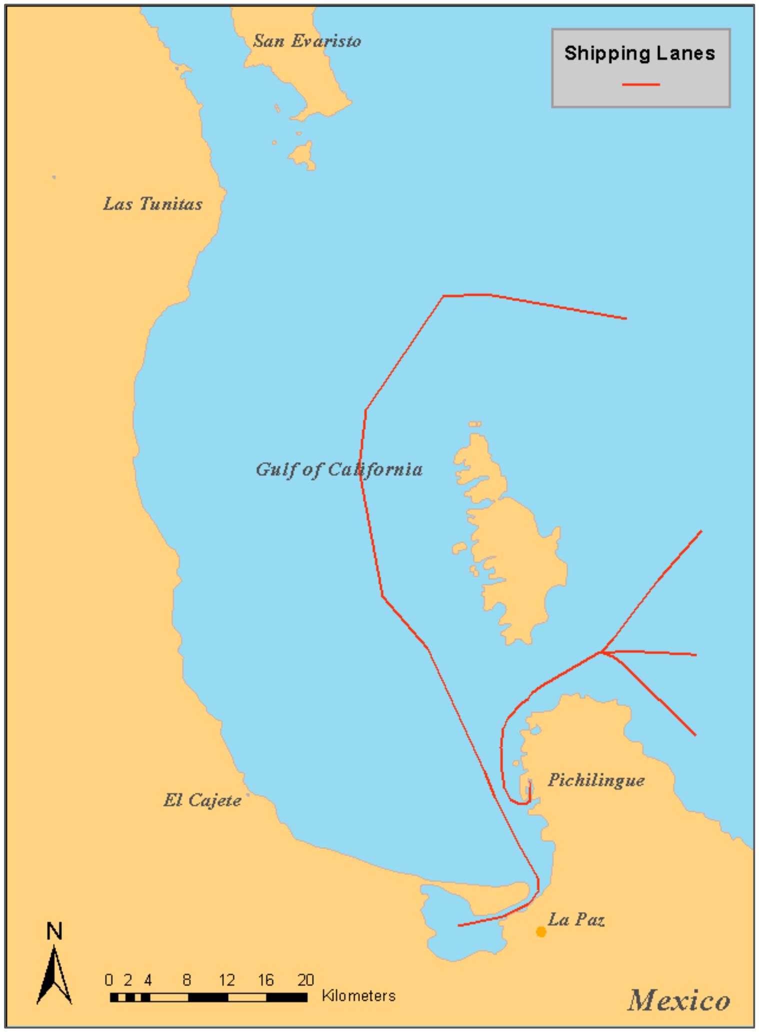

Appendix A2. Benthic Slope –La Paz



Appendix A3. Marine Reserves—La Paz

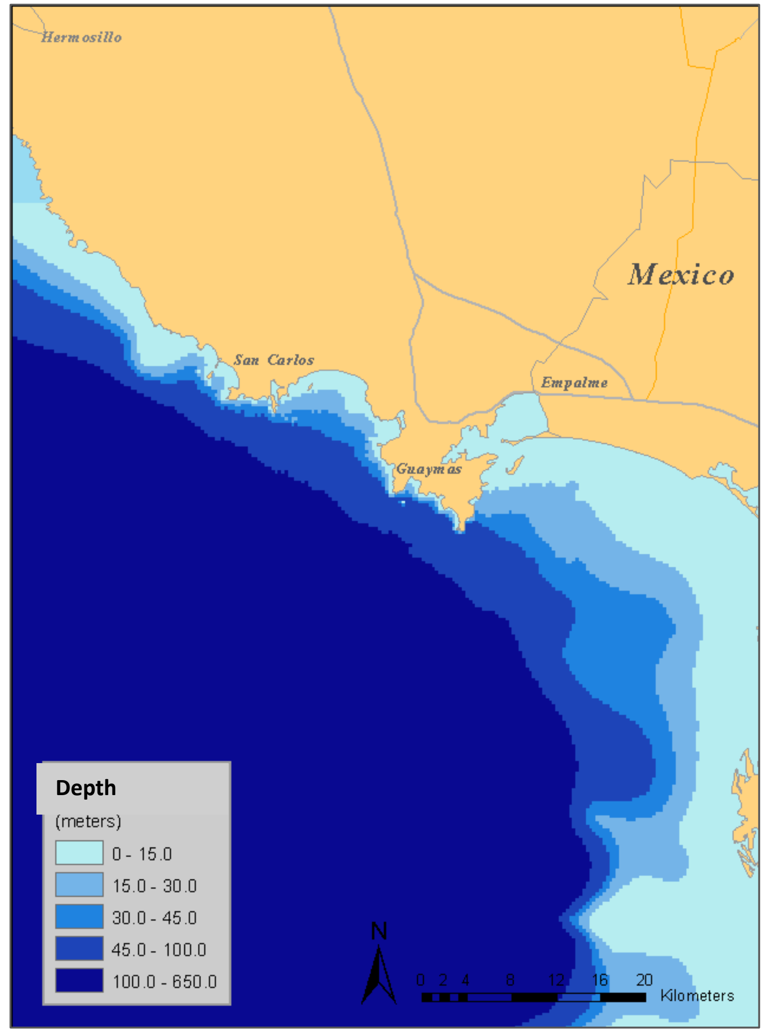



Appendix A4. Shipping Routes—La Paz

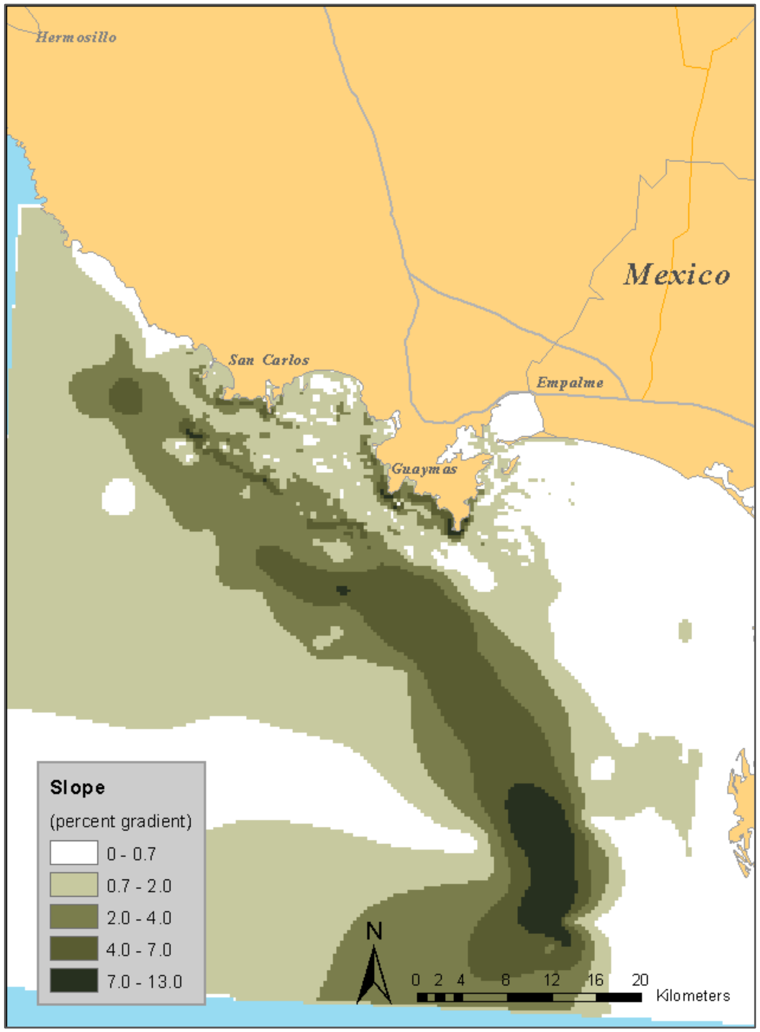


Appendix A5. Existing Aquaculture—La Paz


Appendix A6. Depth—Guaymas



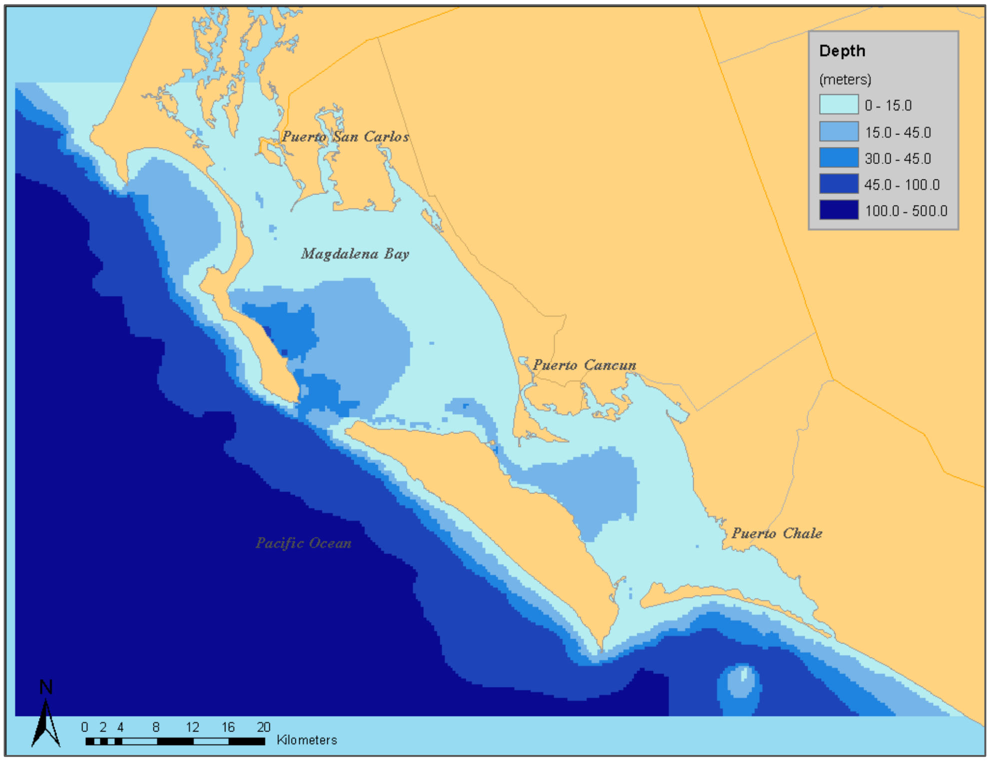
Appendix A7. Benthic Slope—Guaymas



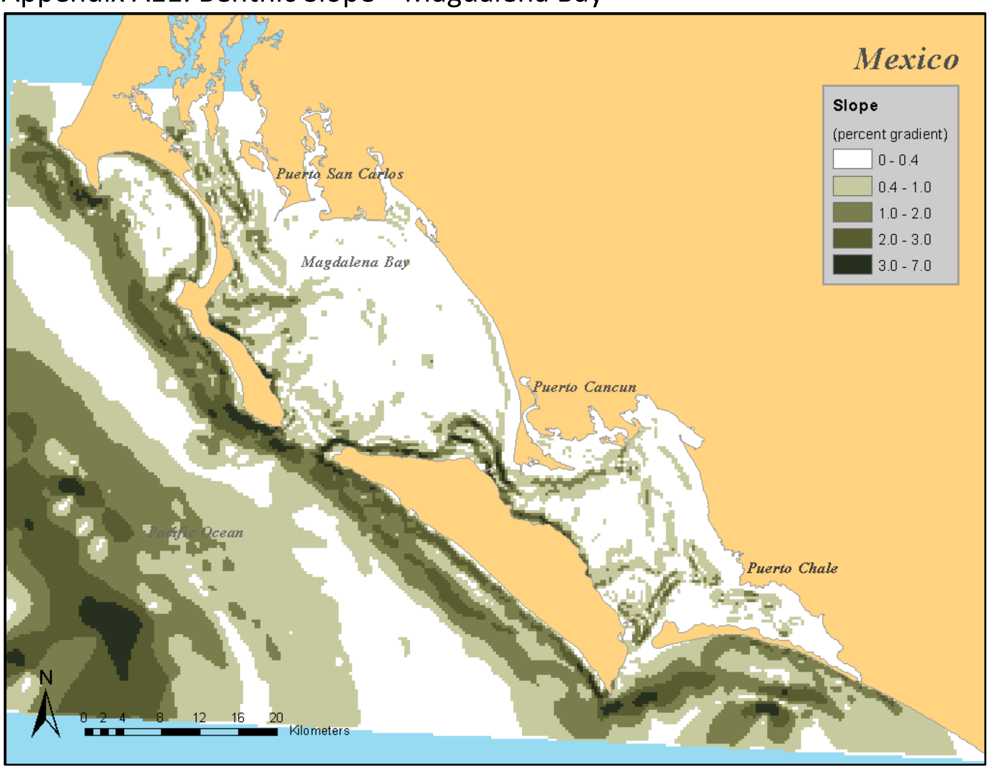

Appendix A8. Shipping Routes—Guaymas

Appendix A9. Existing Aquaculture—Guaymas

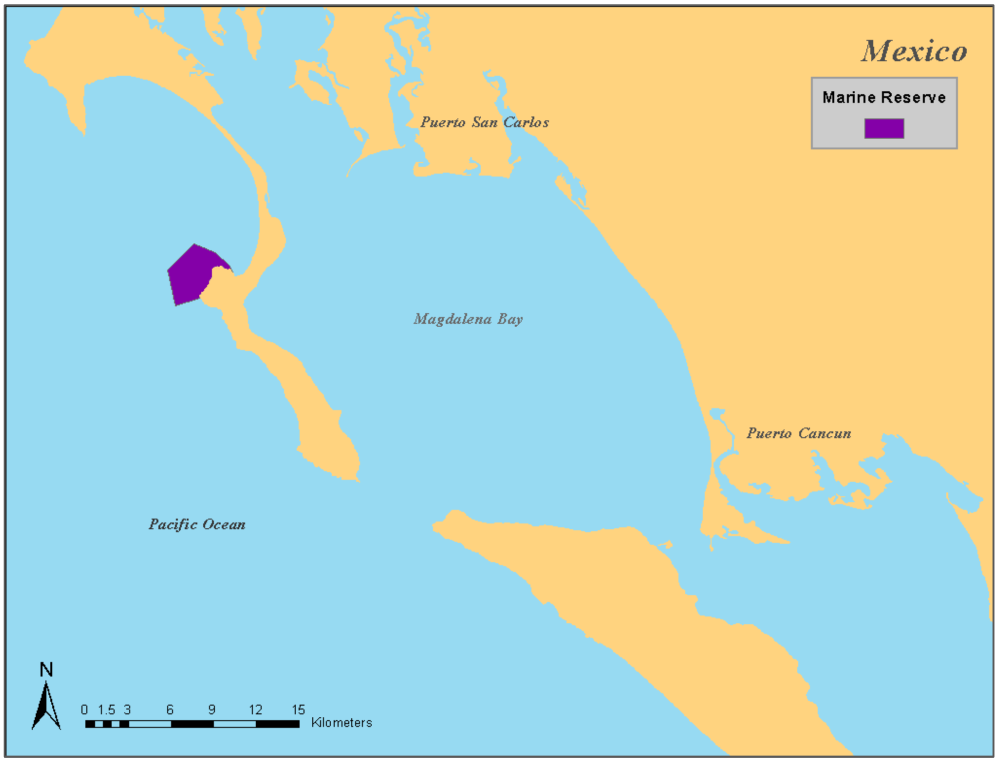
Appendix A10. Depth—Magdalena Bay



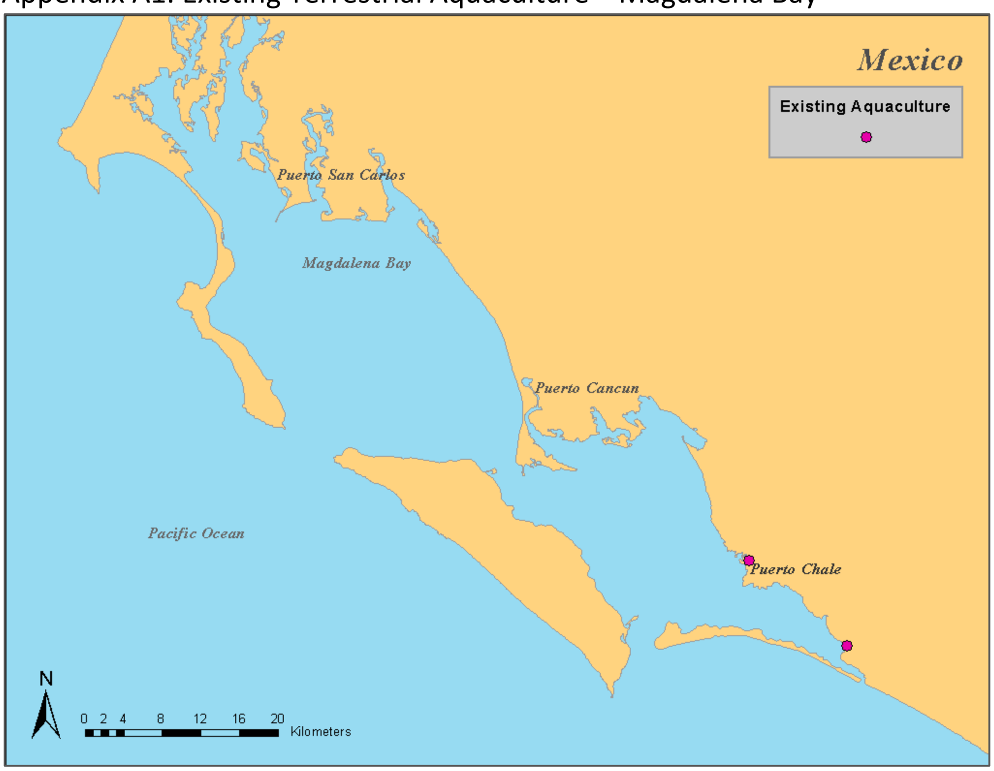

Appendix A11. Benthic Slope—Magdalena Bay



Appendix A12. Marine Reserves—Magdalena Bay



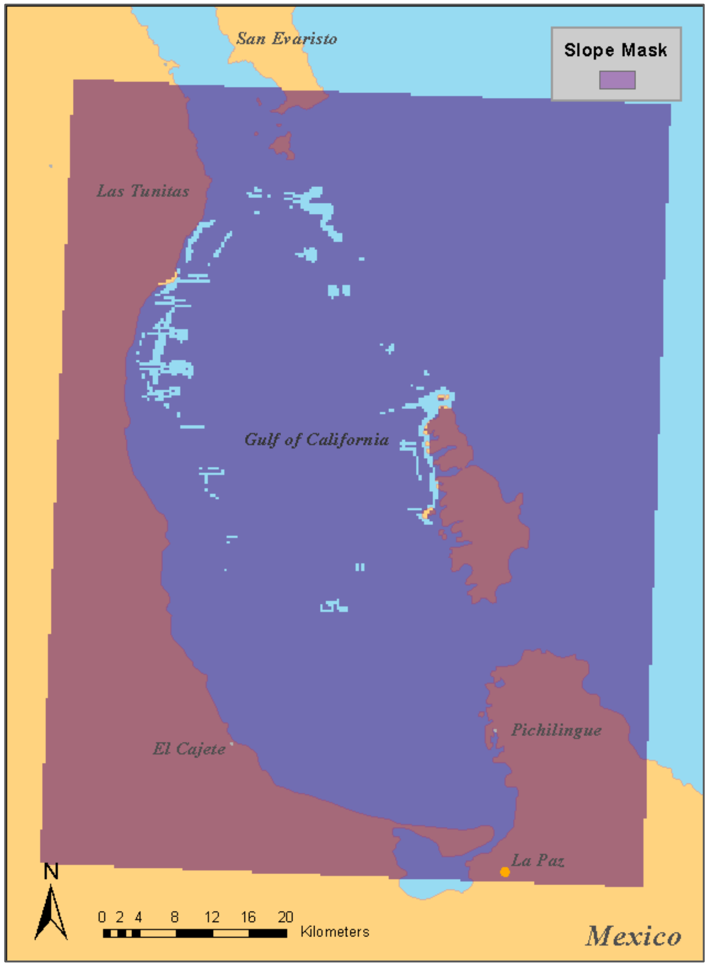

Appendix A1. Existing Terrestrial Aquaculture—Magdalena Bay



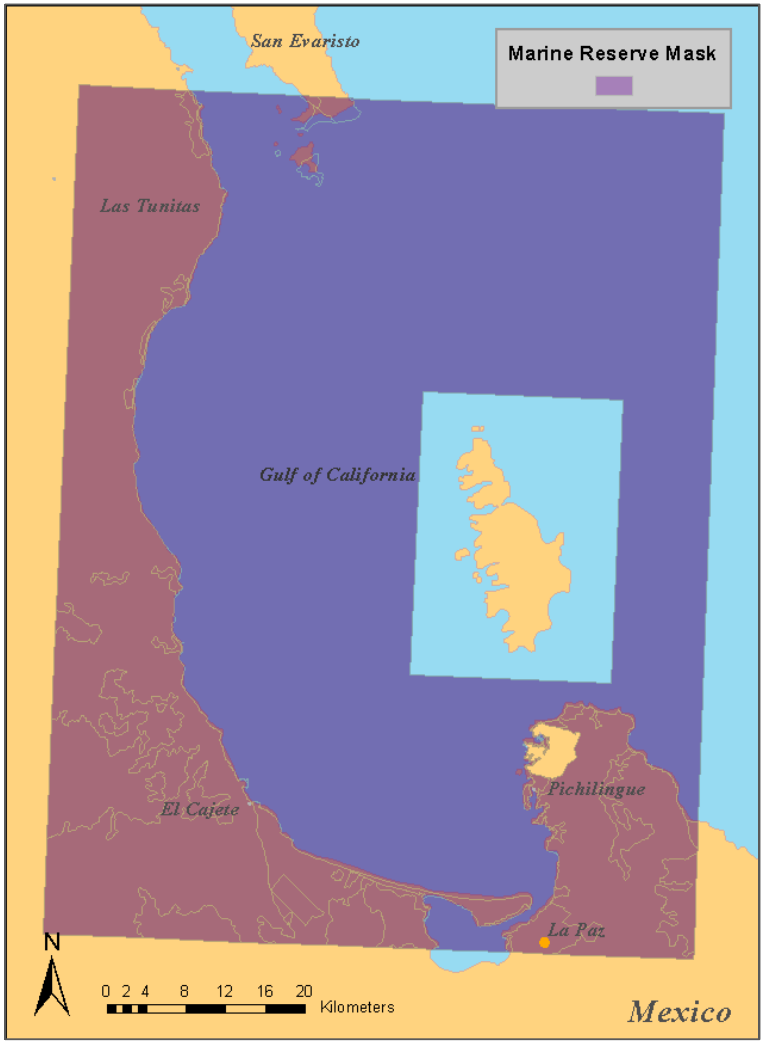
## B. Maps of Spatial Parameter Masks

Appendix B1. Depth Mask—La Paz Artisanal

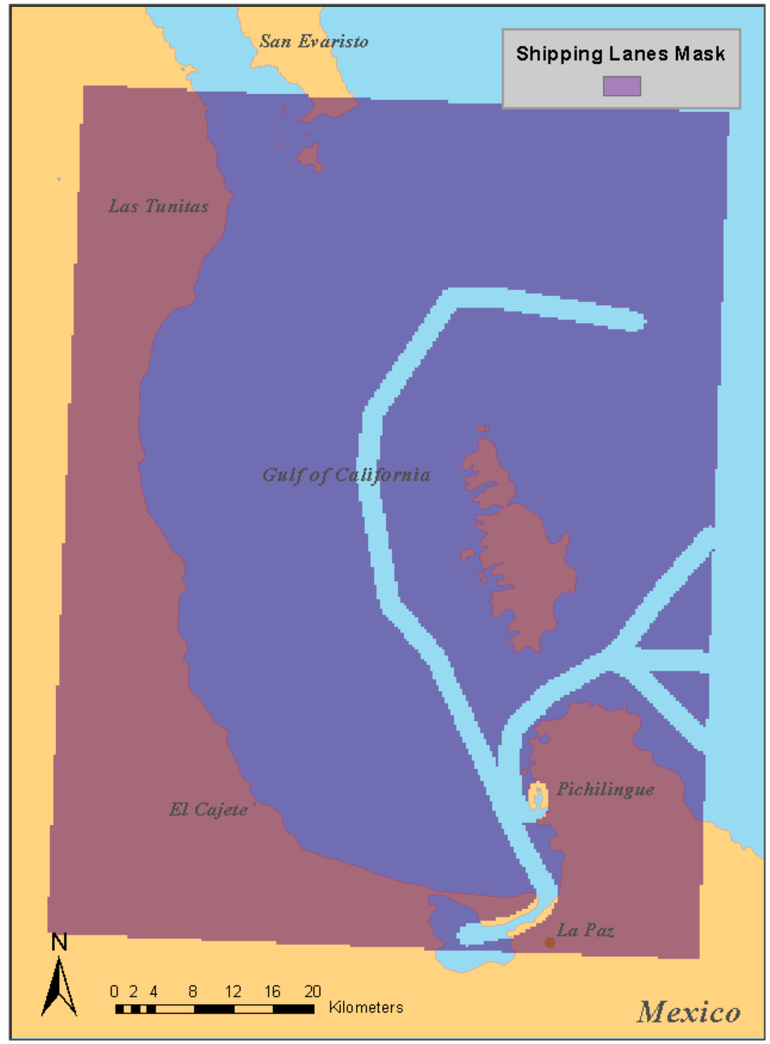

Appendix B2. Benthic Slope Mask—La Paz Artisanal



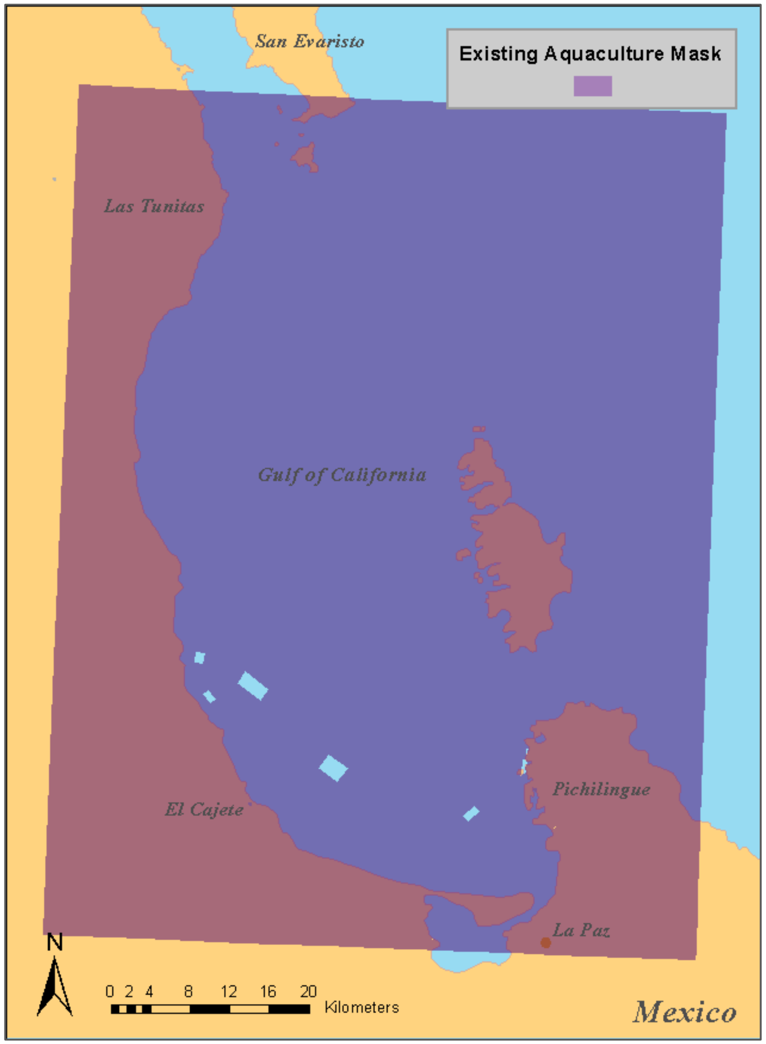
Appendix B3. Marine Reserves Mask—La Paz Artisanal



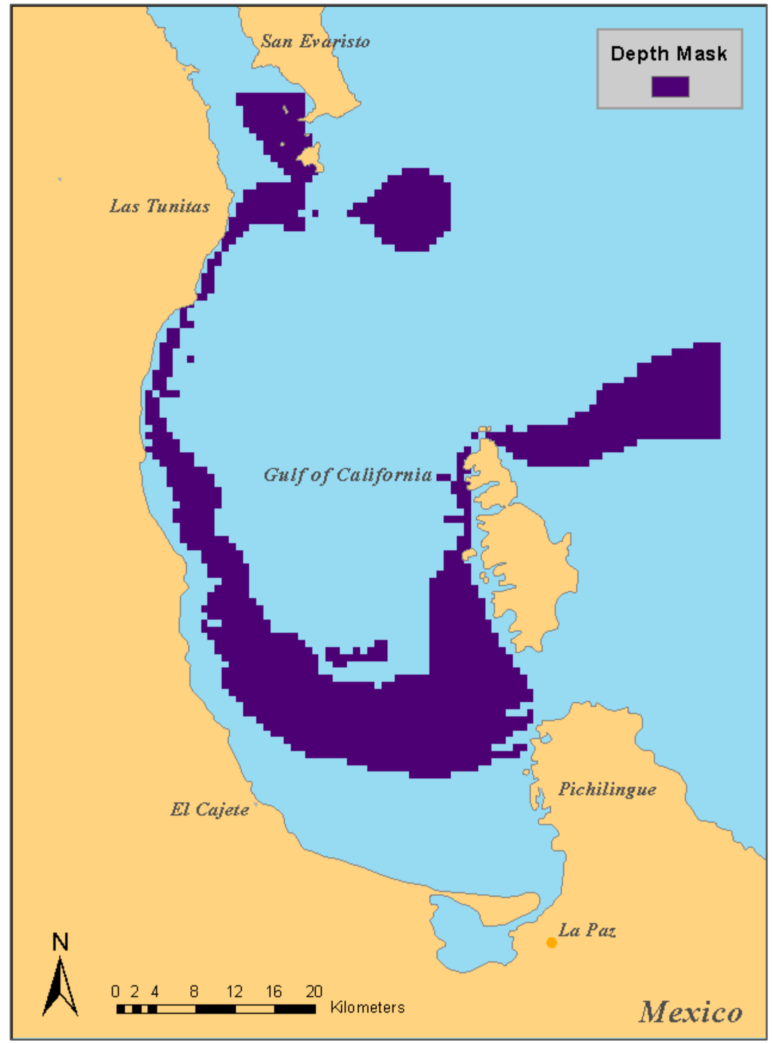

Appendix B4. Shipping Lanes Mask—La Paz Artisanal



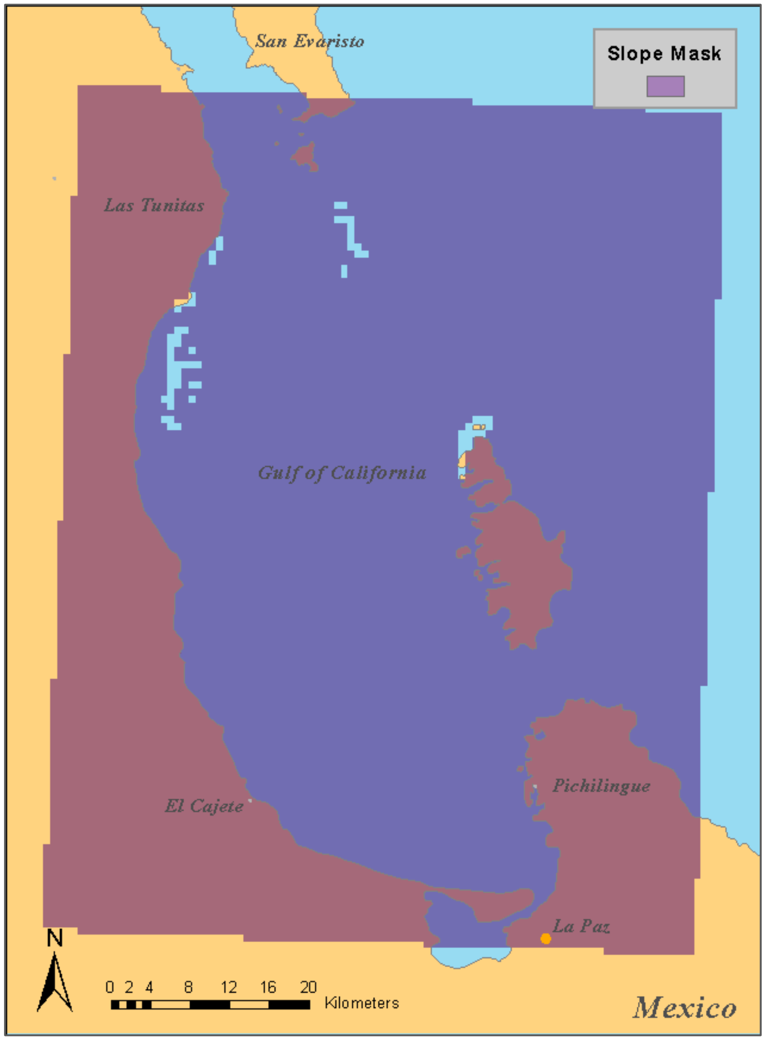
Appendix B5. Existing Aquaculture Mask—La Paz Artisanal




Appendix B6. Depth Mask—La Paz Industrial

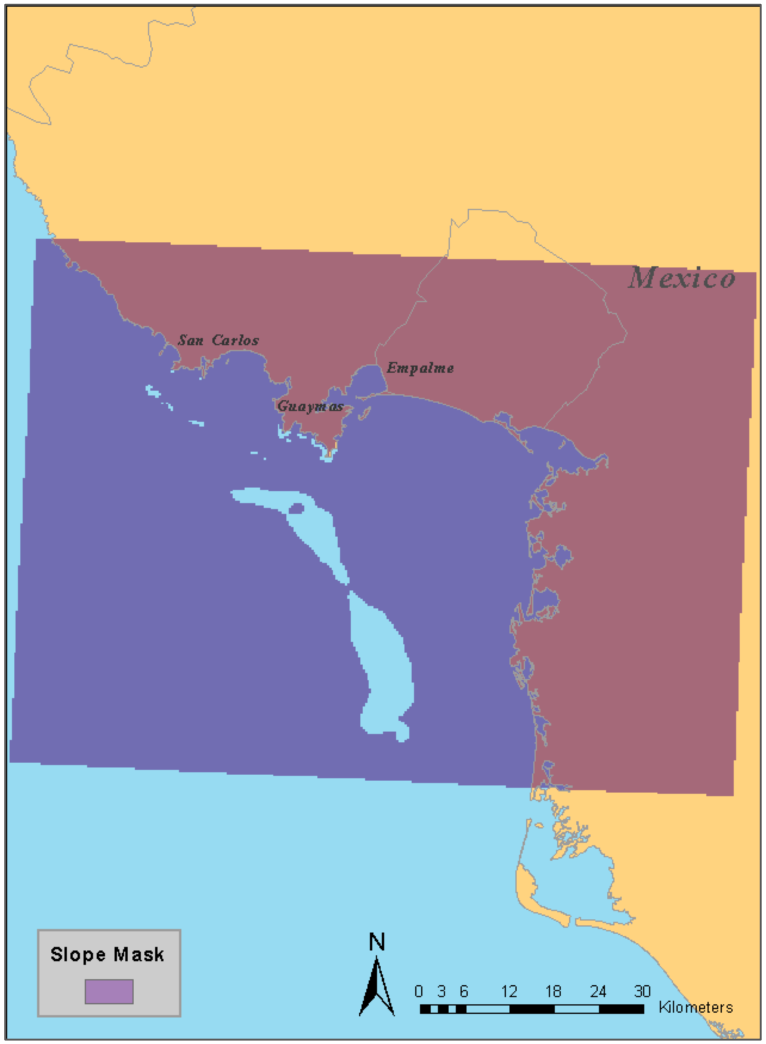


Appendix B7. Benthic Slope Mask—La Paz Industrial

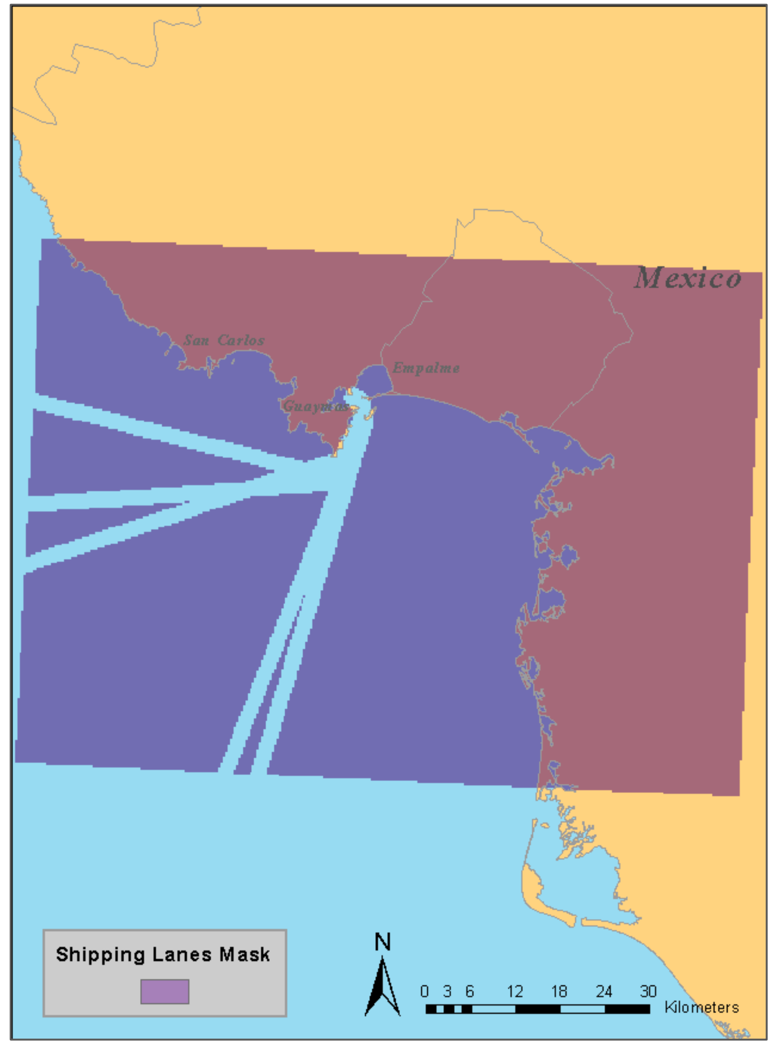



Appendix B8. Depth Mask--Guaymas

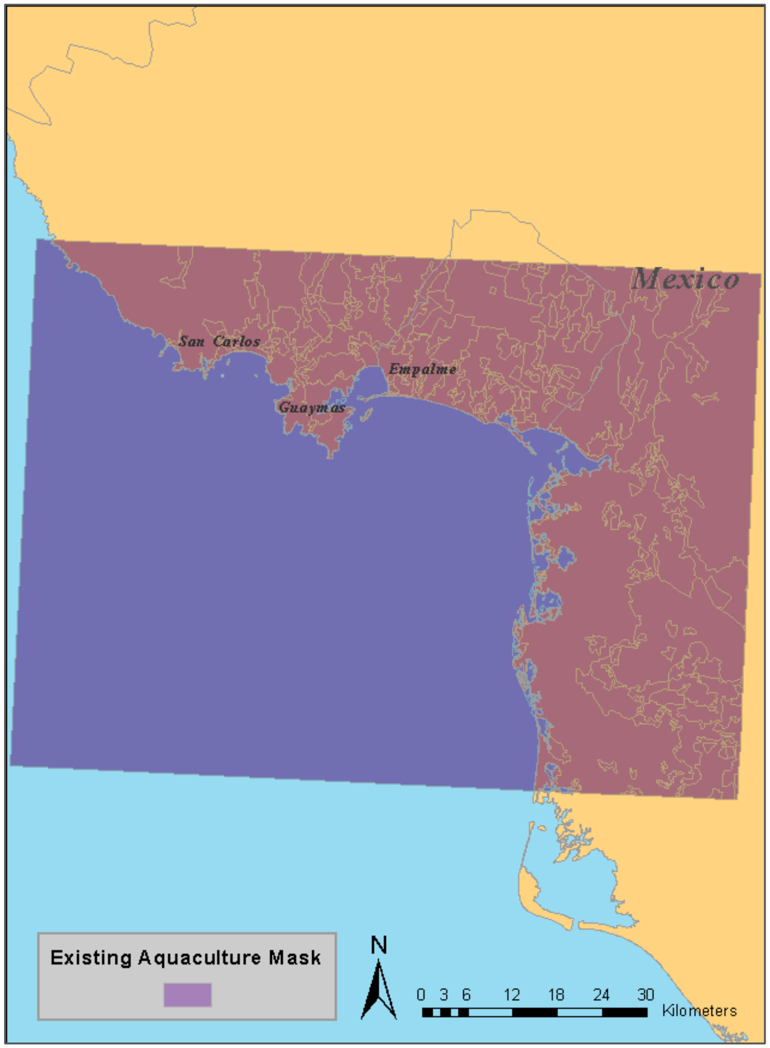
Appendix B9. Benthic Slope Mask—Guaymas



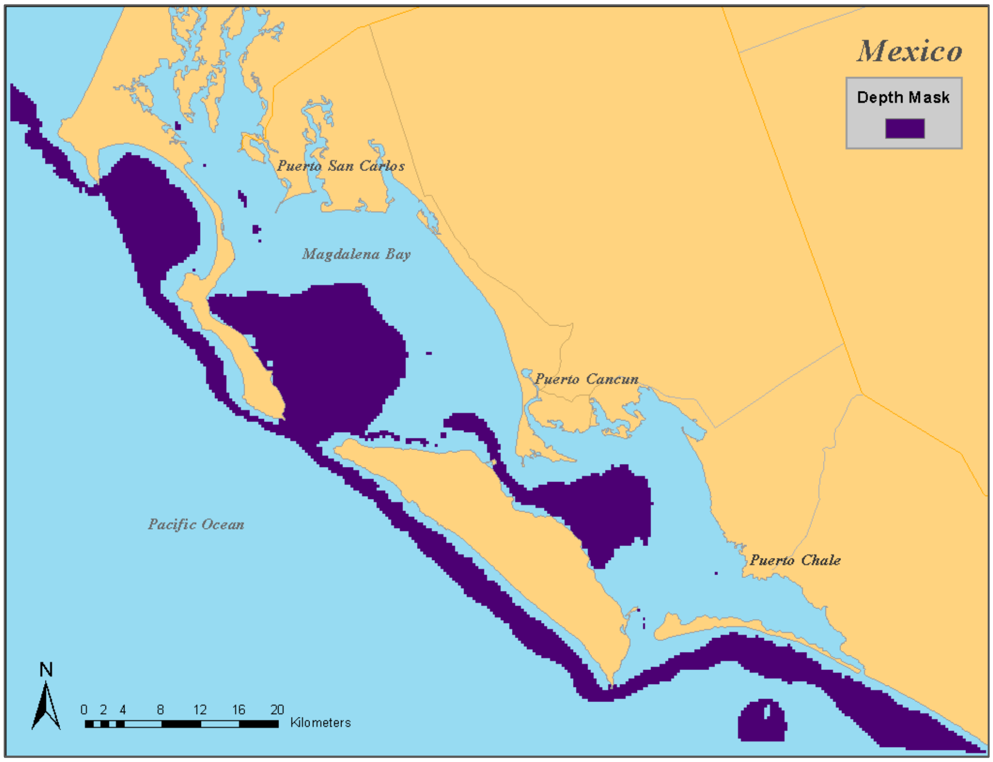

Appendix B10. Shipping Lanes Mask—Guaymas



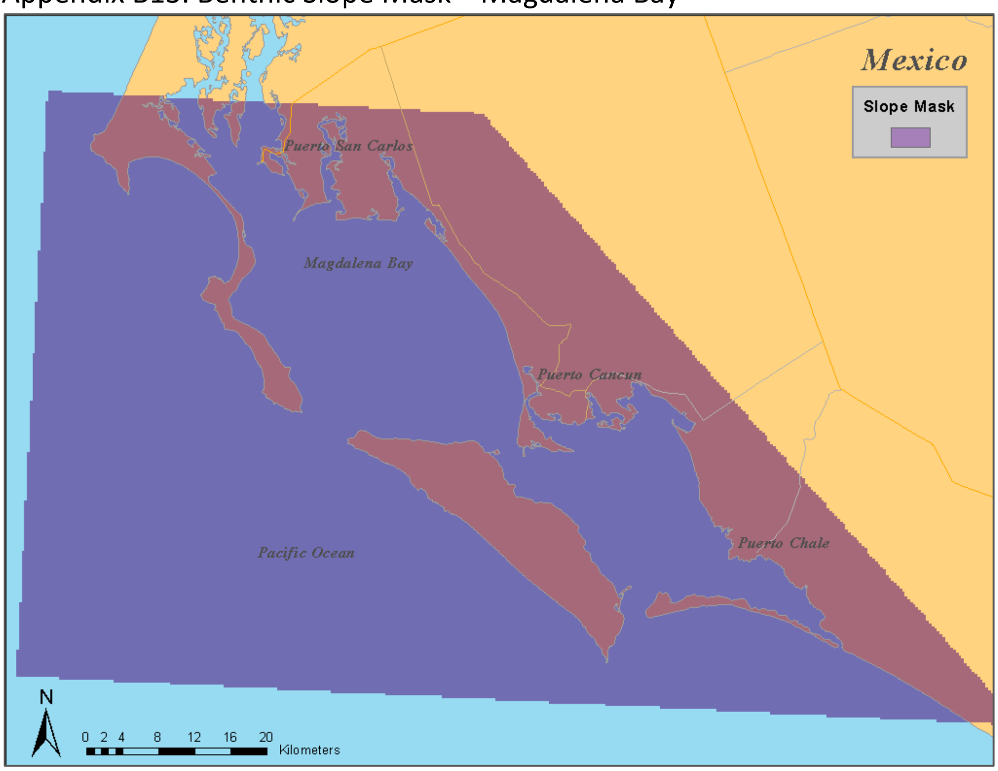
Appendix B11. Existing Aquaculture Mask—Guaymas



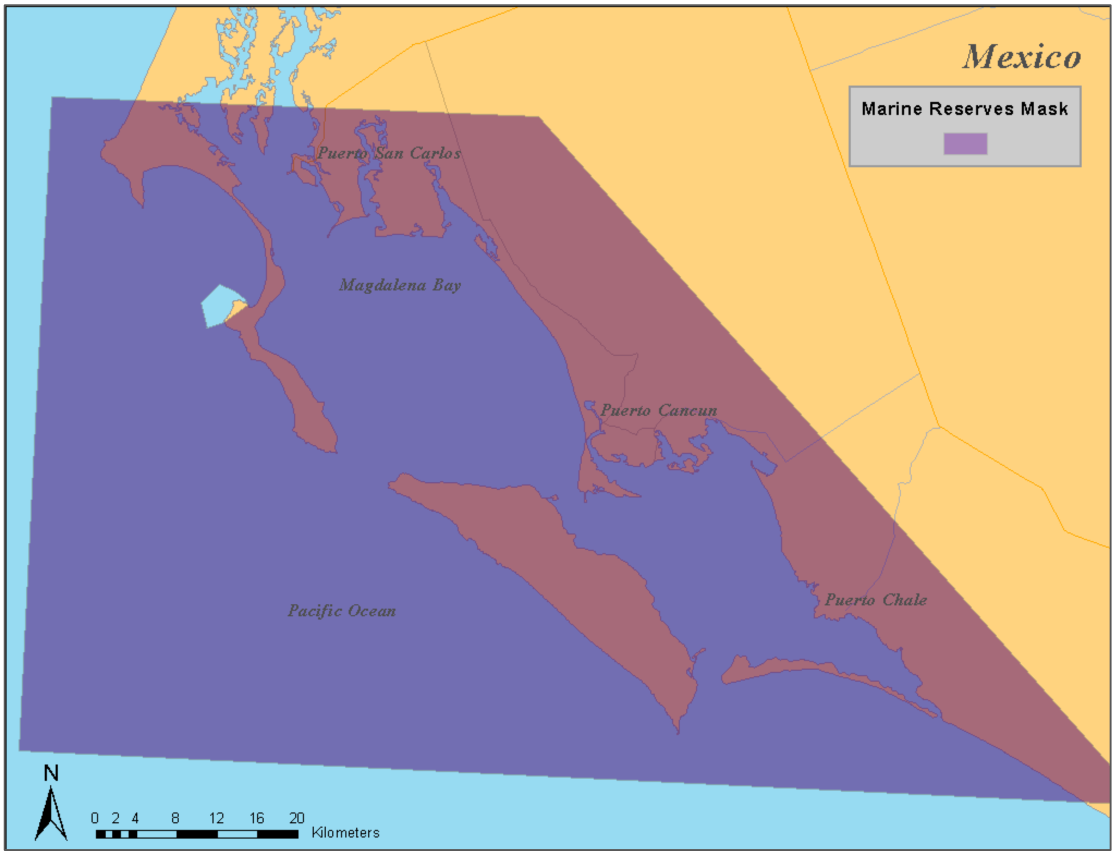
Appendix B12. Depth Mask—Magdalena Bay




Appendix B13. Benthic Slope Mask—Magdalena Bay

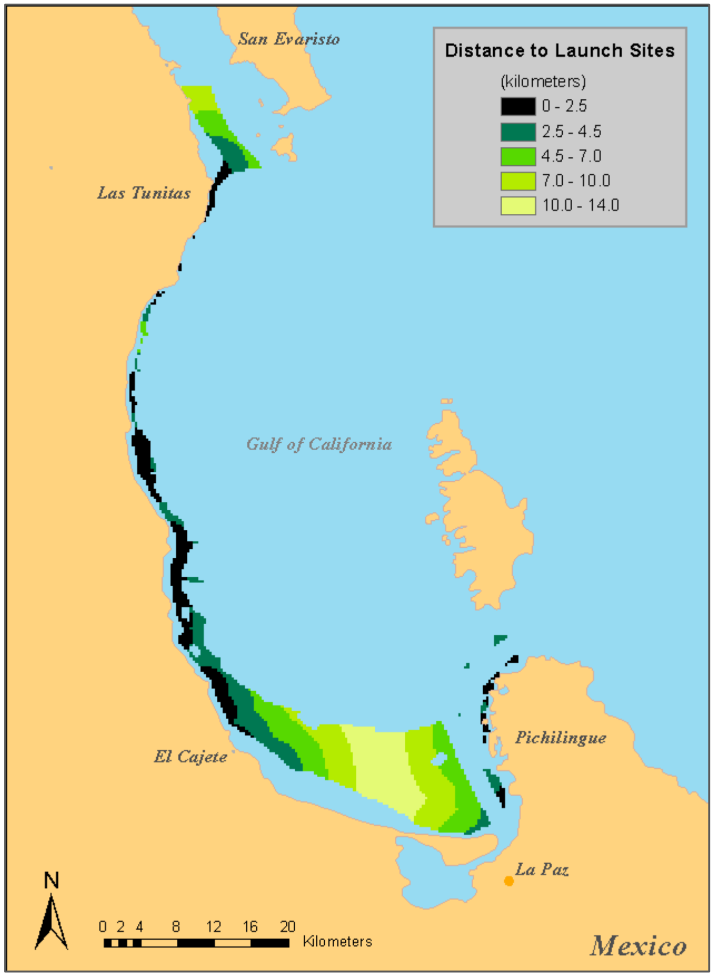


Appendix B14. Marine Reserves Mask—Magdalena Bay

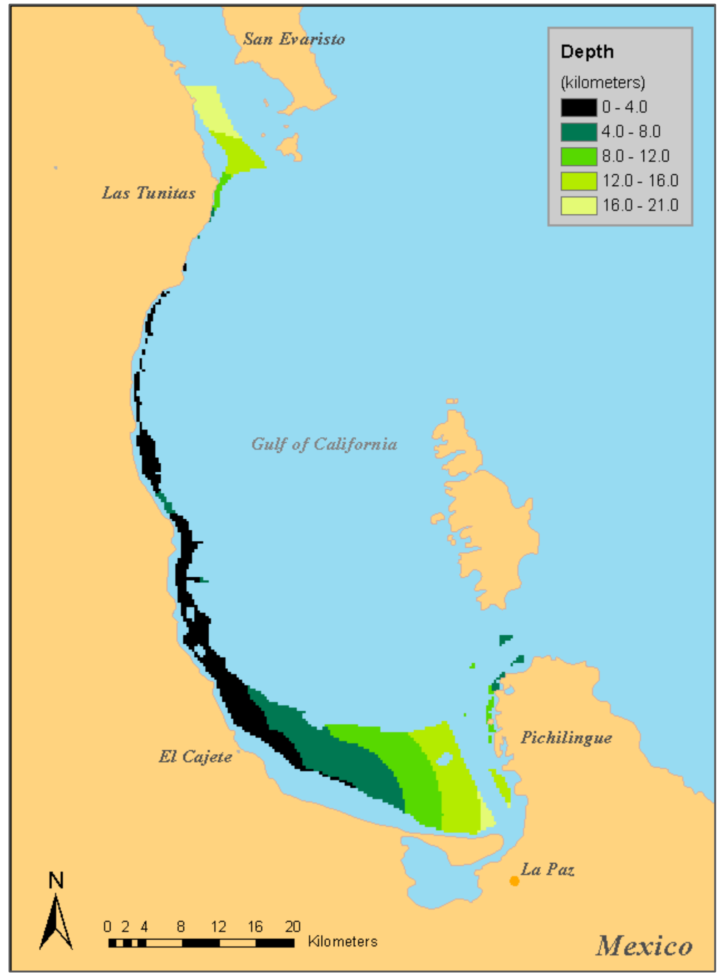


## C. Maps of Spatial Parameter Inputs for Spatial Bio-Economic Model

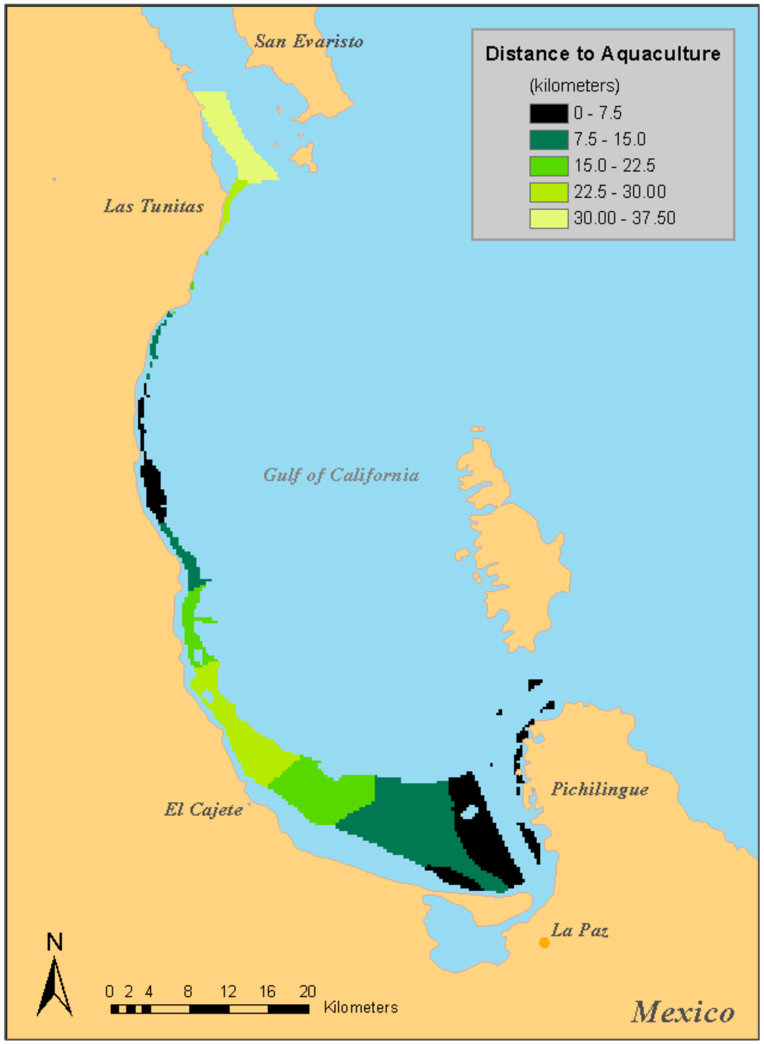
Appendix C1. Distance to Launch Sites—La Paz Artisanal



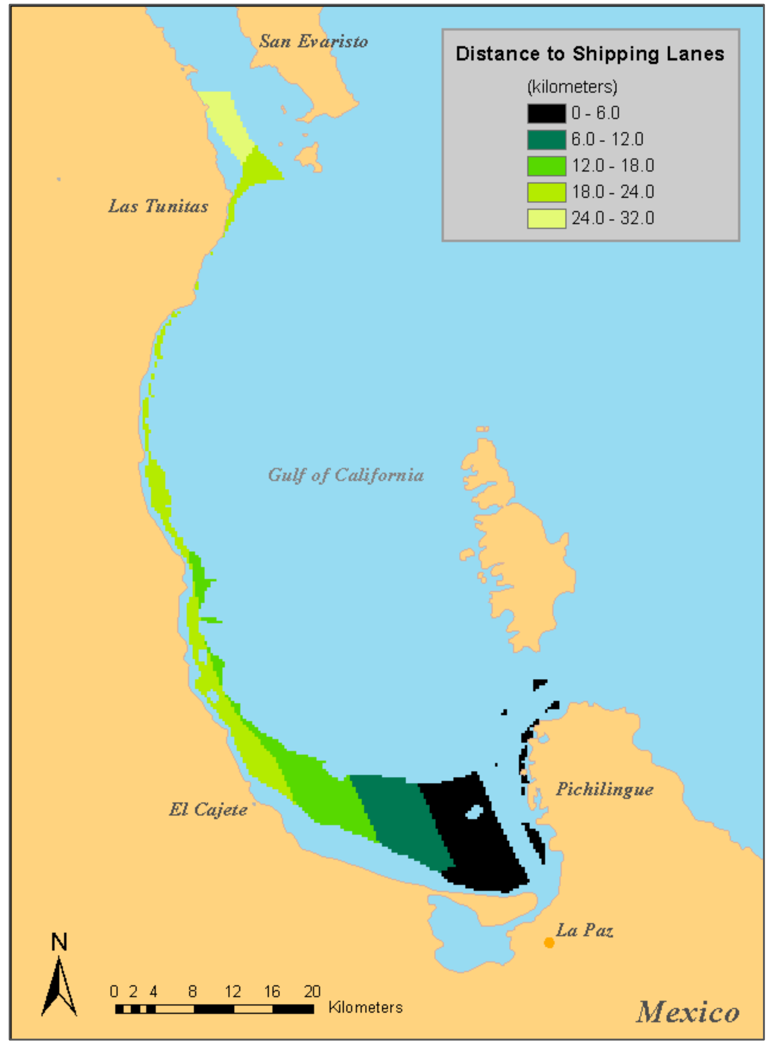

Appendix C2. Distance to Pollution—La Paz Artisanal



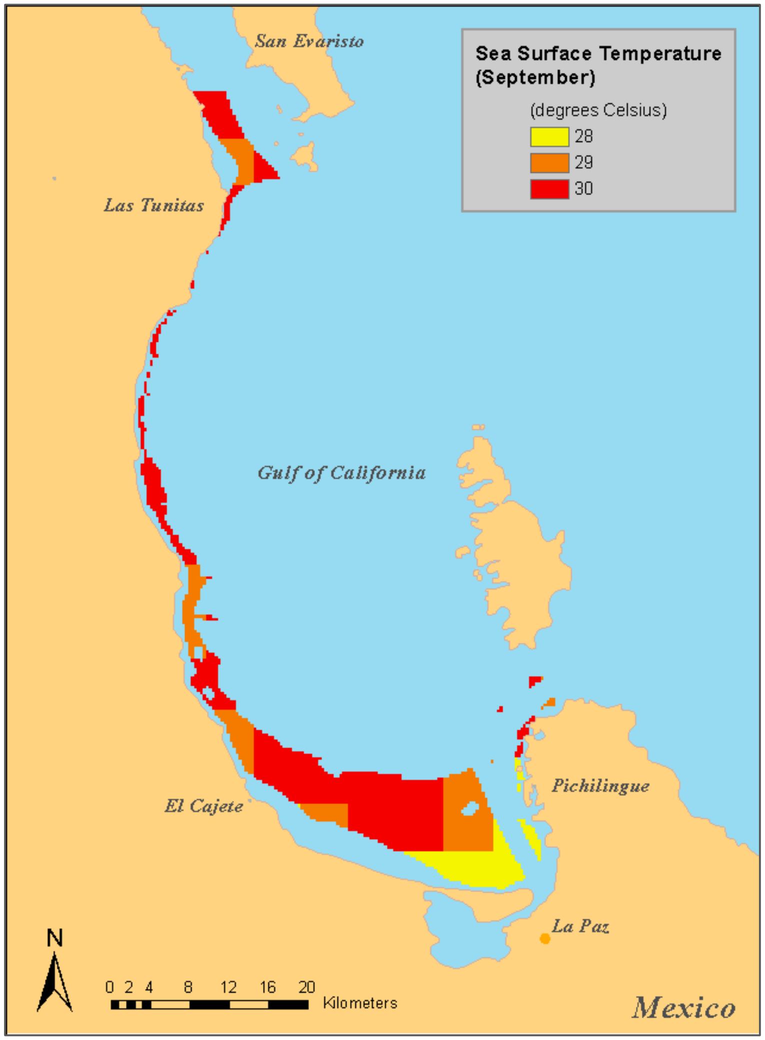
Appendix C3. Distance to Aquaculture—La Paz Artisanal



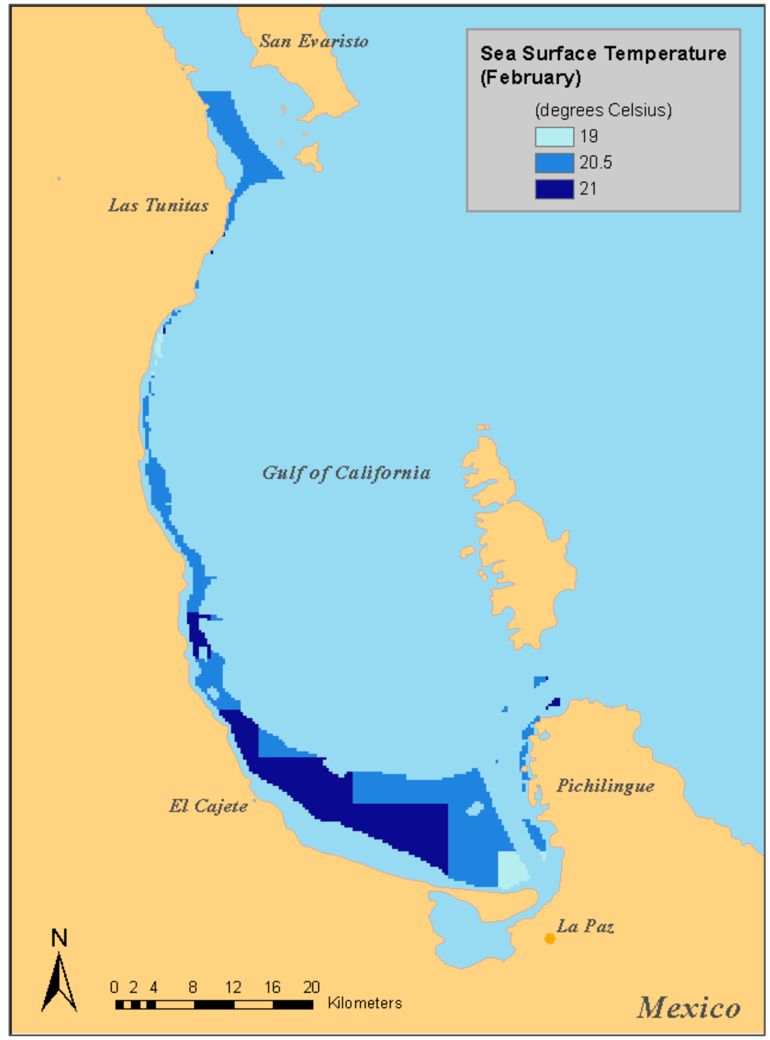

Appendix C4. Distance to Shipping Lanes—La Paz Artisanal



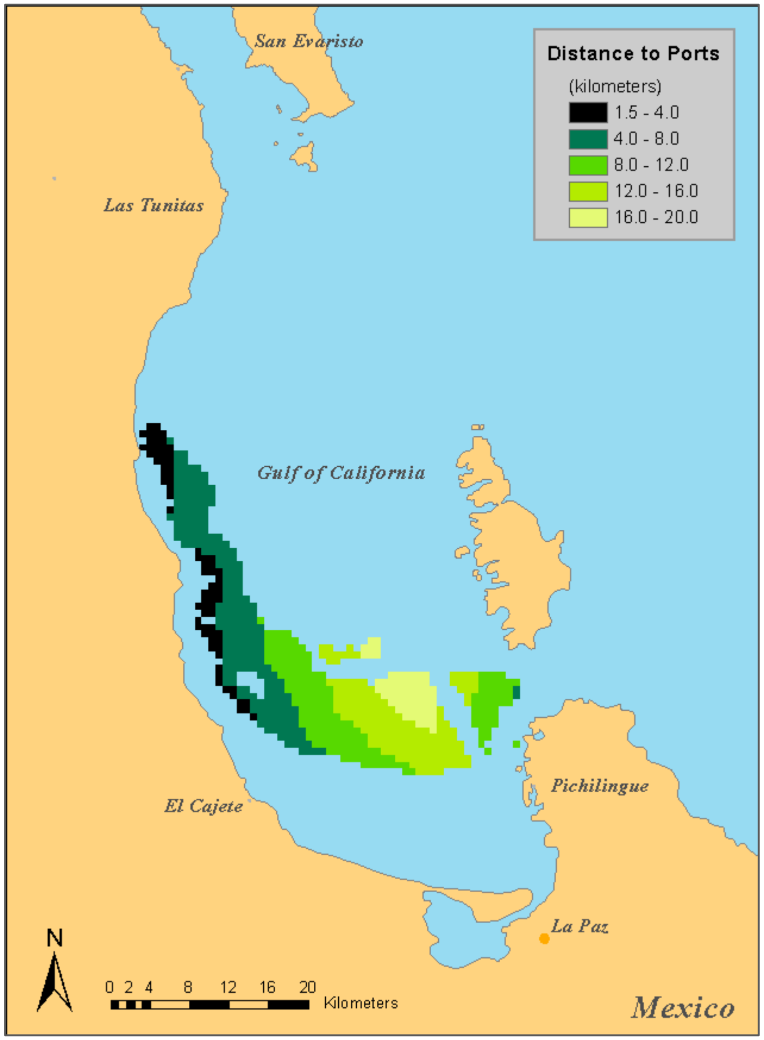
Appendix C5. SST September (warm)—La Paz Artisanal



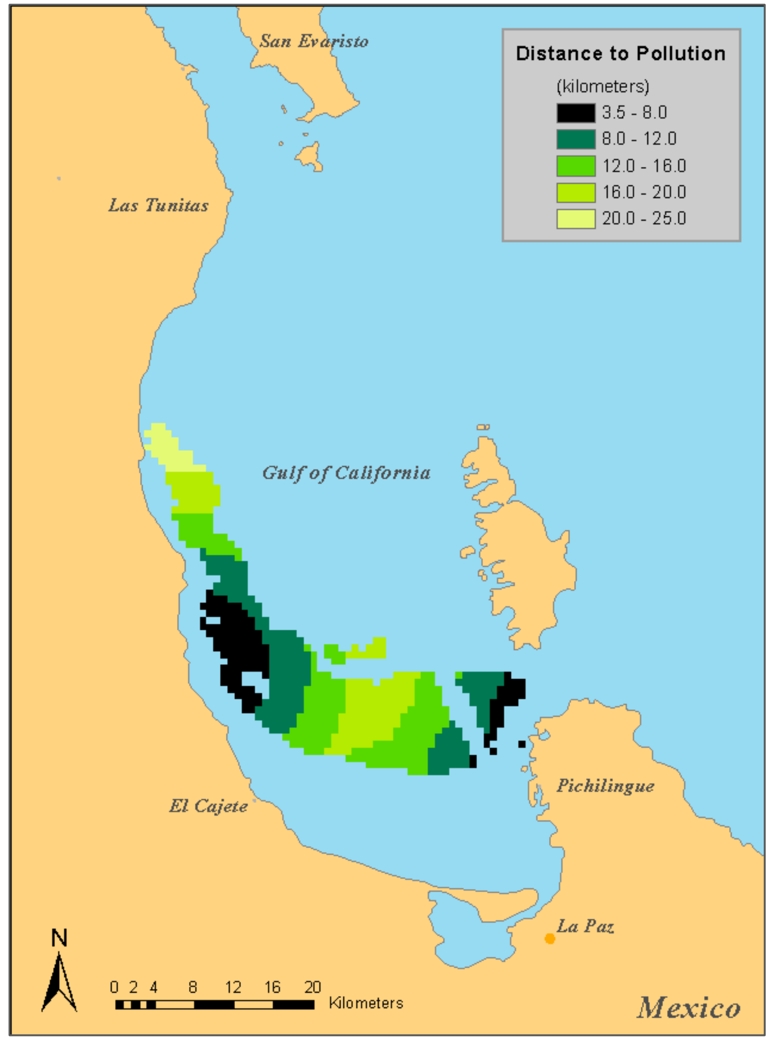

Appendix C6. SST February (cold)—La Paz Artisanal



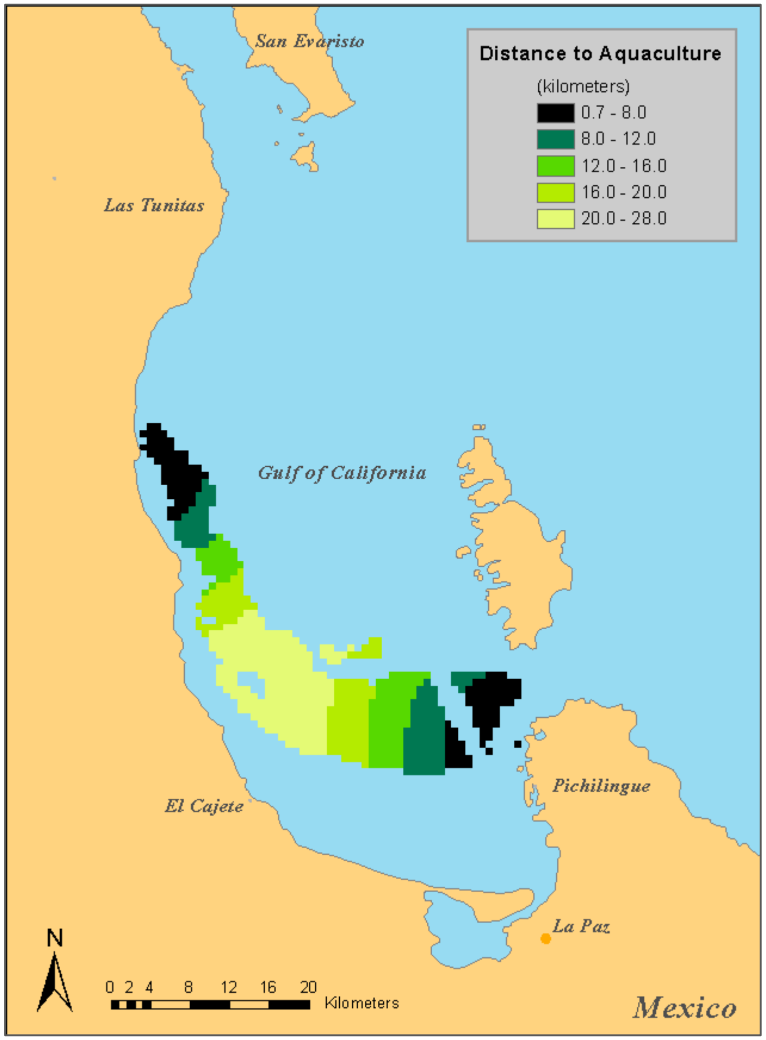
Appendix C7. Distance to Ports—La Paz Industrial



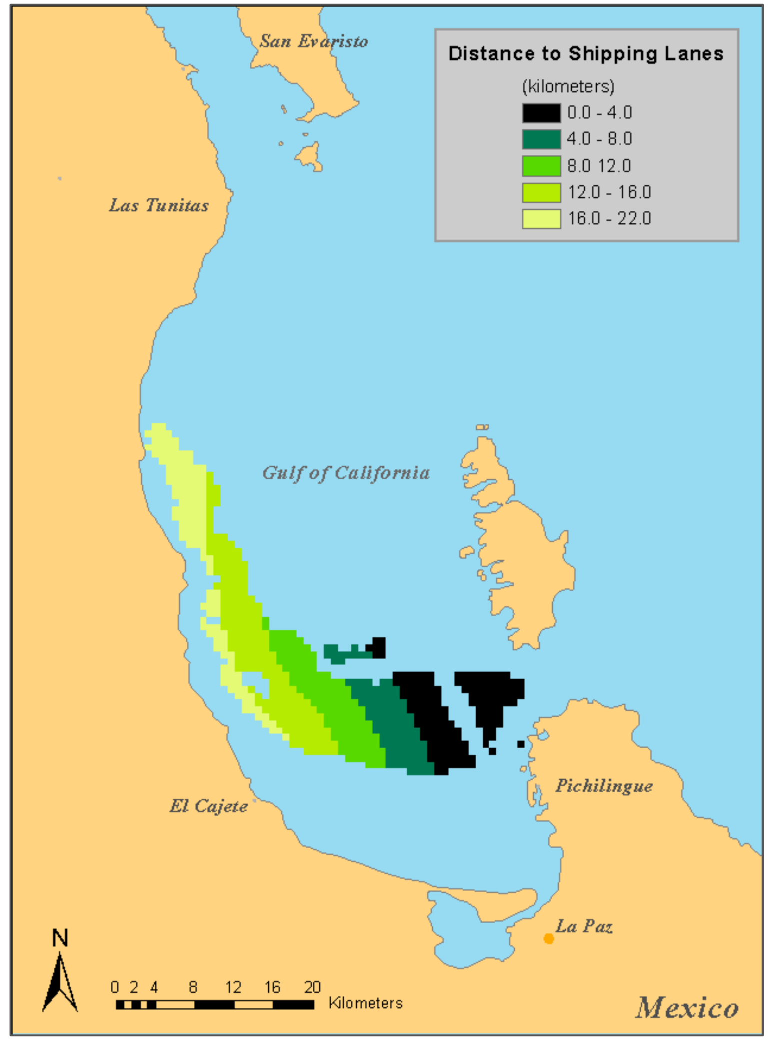

Appendix C8. Distance to Pollution—La Paz Industrial



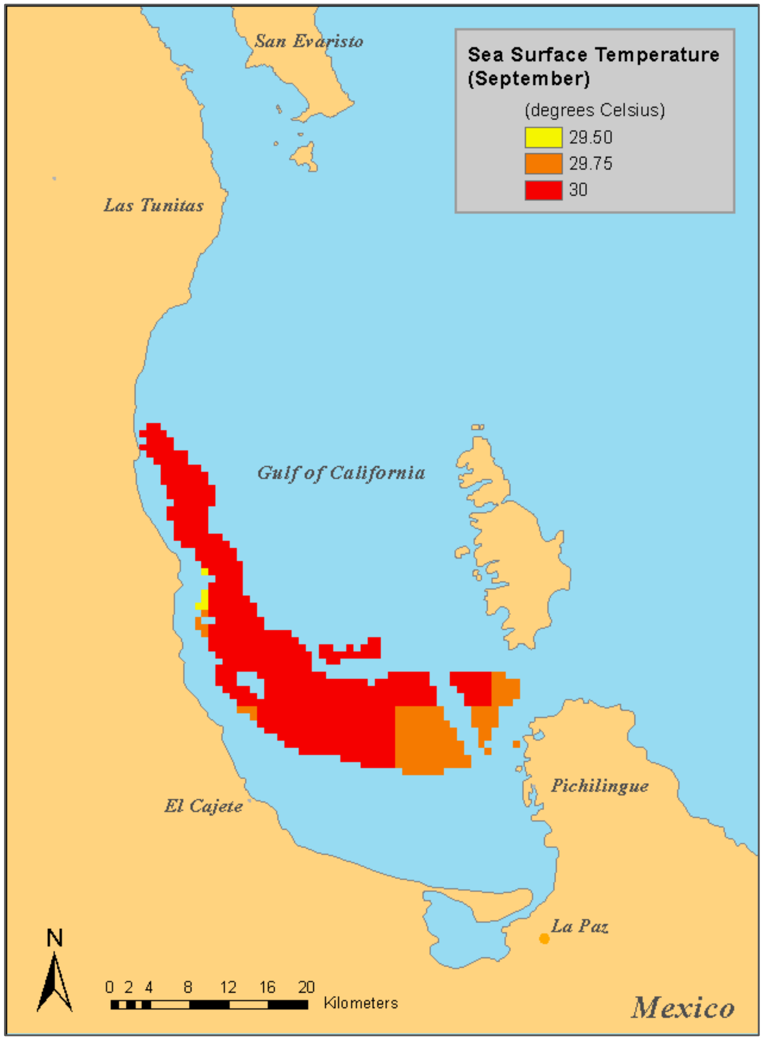
Appendix C9. Distance to Aquaculture—La Paz Industrial



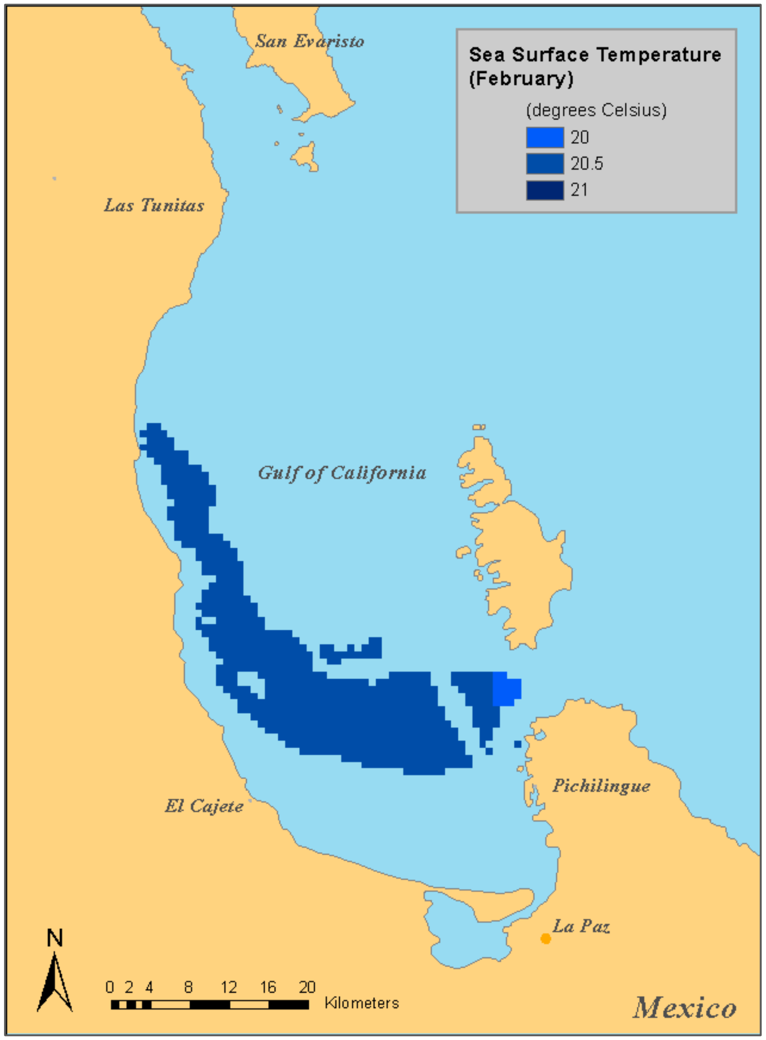

Appendix C10. Dist. to Shipping Lanes—La Paz Industrial



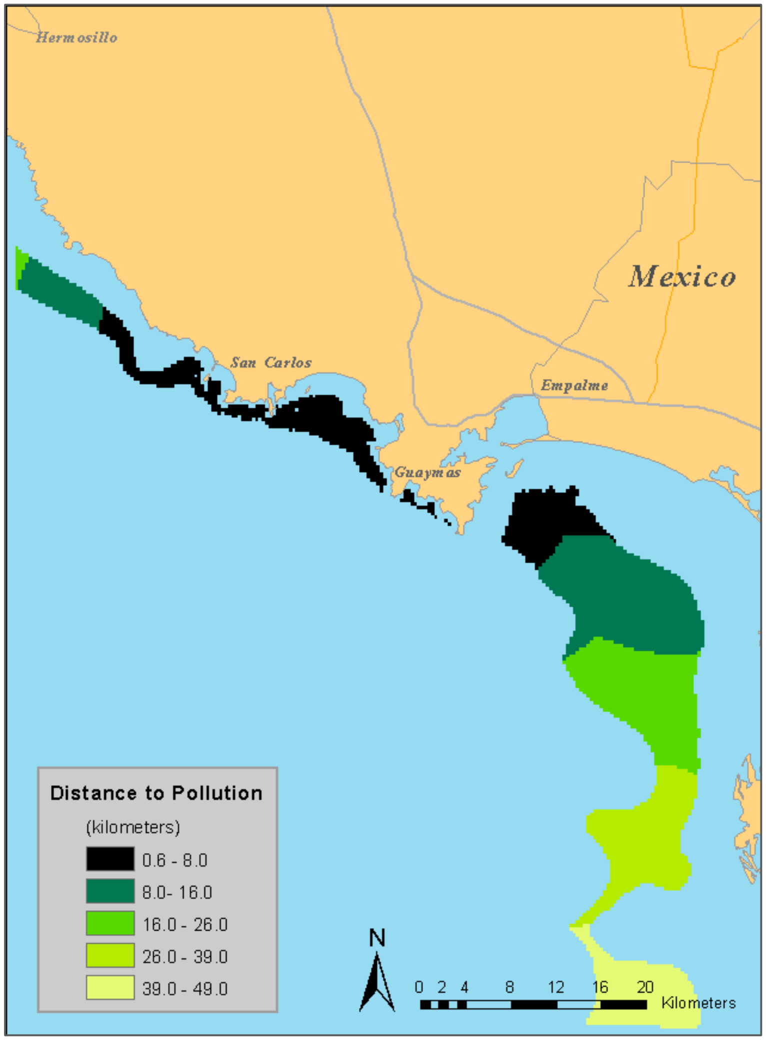
Appendix C11. SST September (warm)—La Paz Industrial



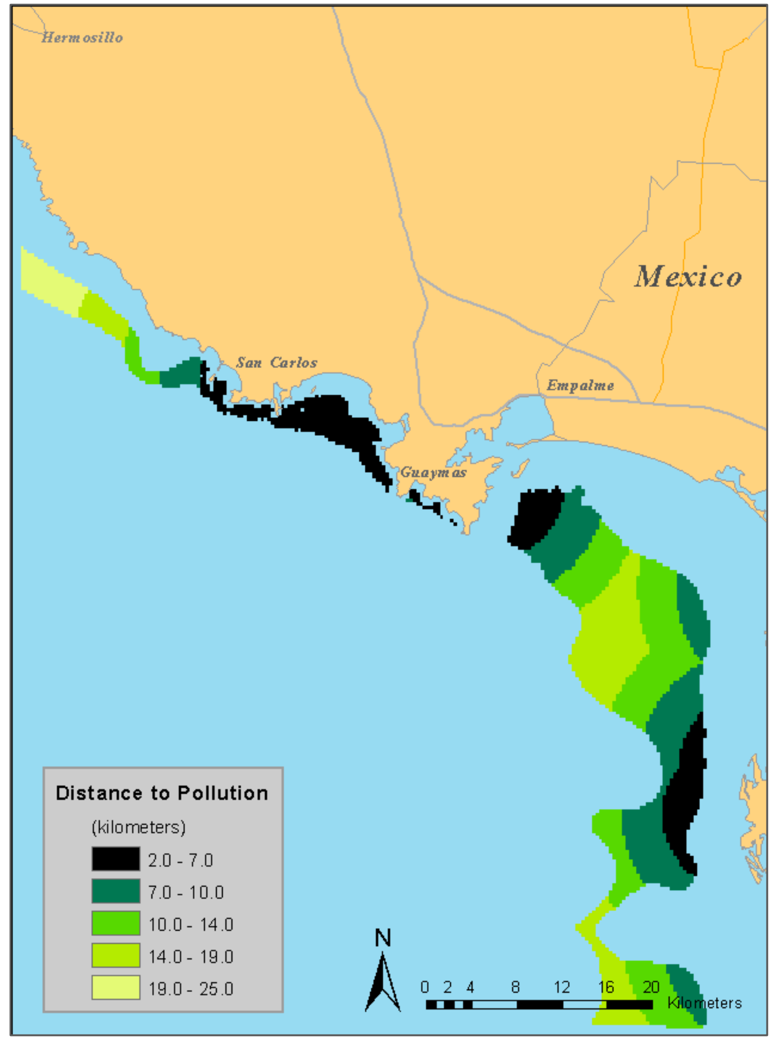

Appendix C12. SST February (cold)—La Paz Industrial



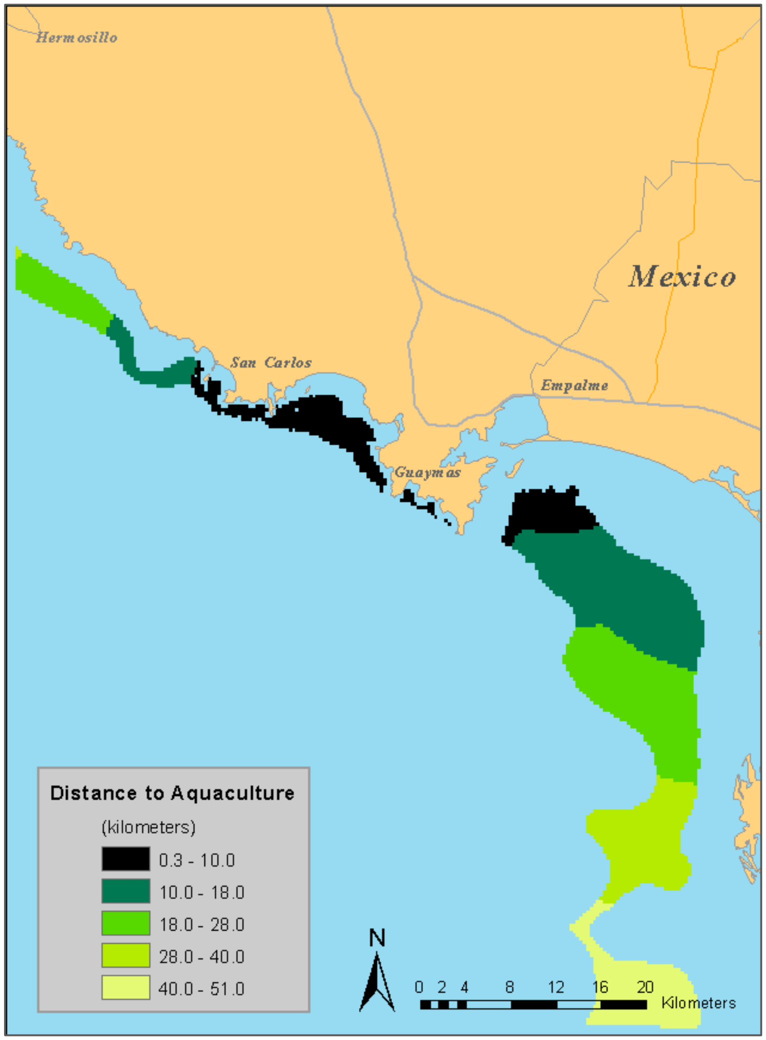
Appendix C13. Distance to Launch Sites—Guaymas



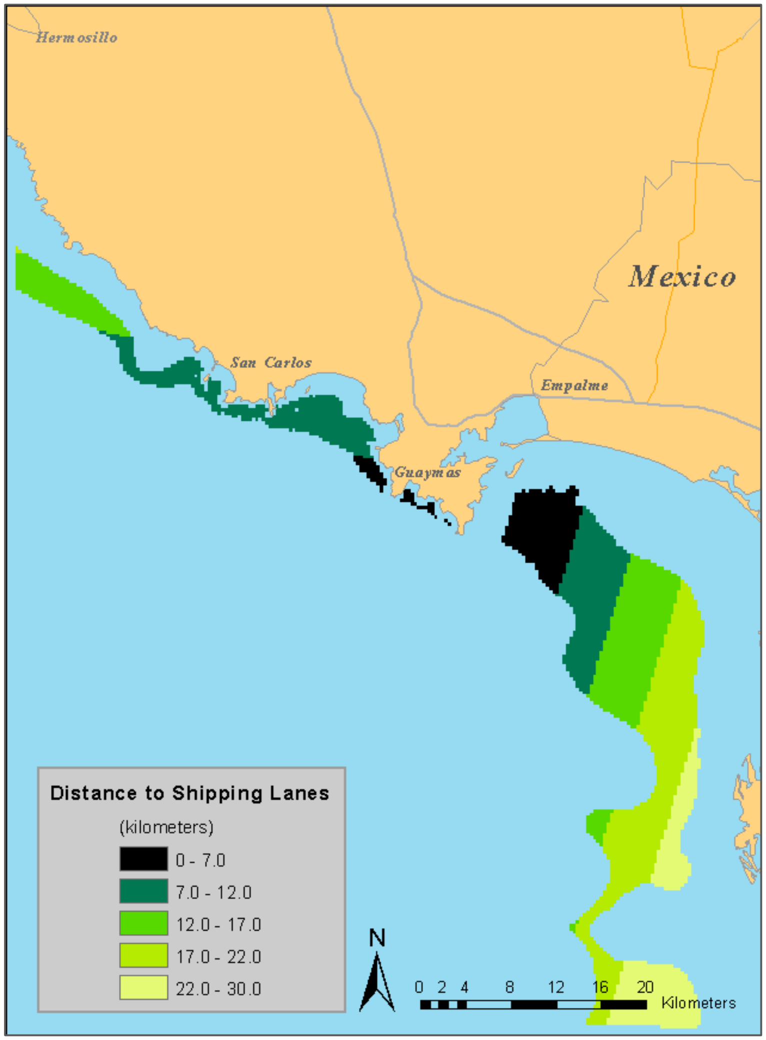

Appendix C14. Distance to Pollution—Guaymas



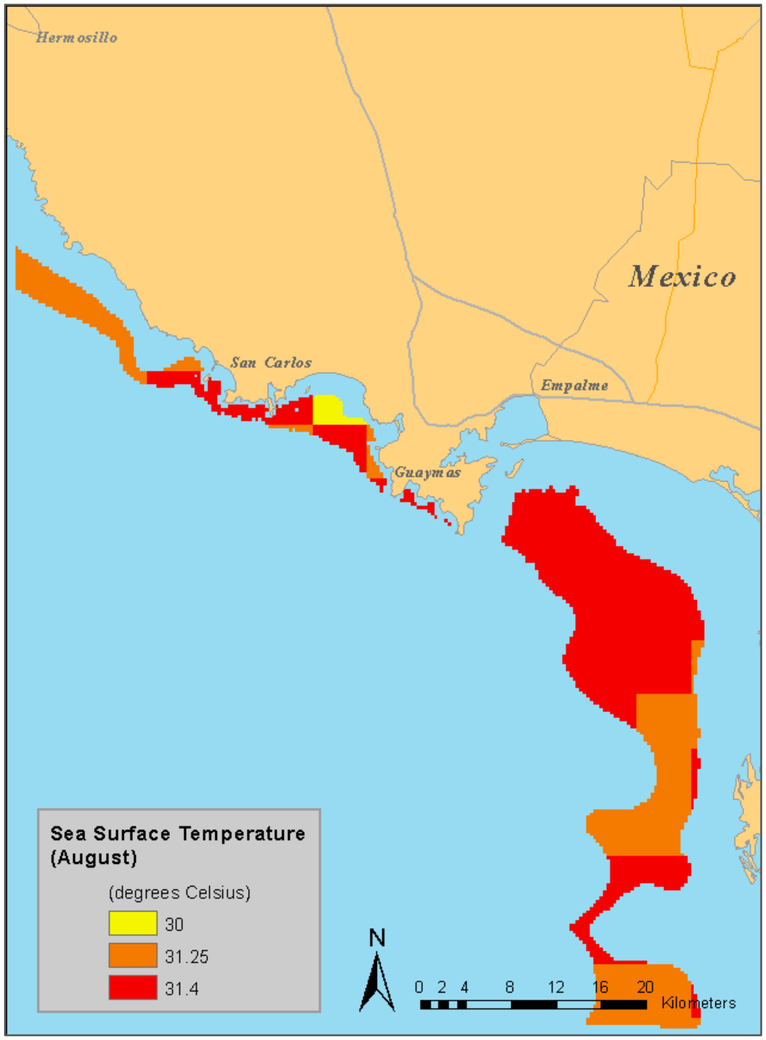
Appendix C15. Distance to Existing Aquaculture—Guaymas



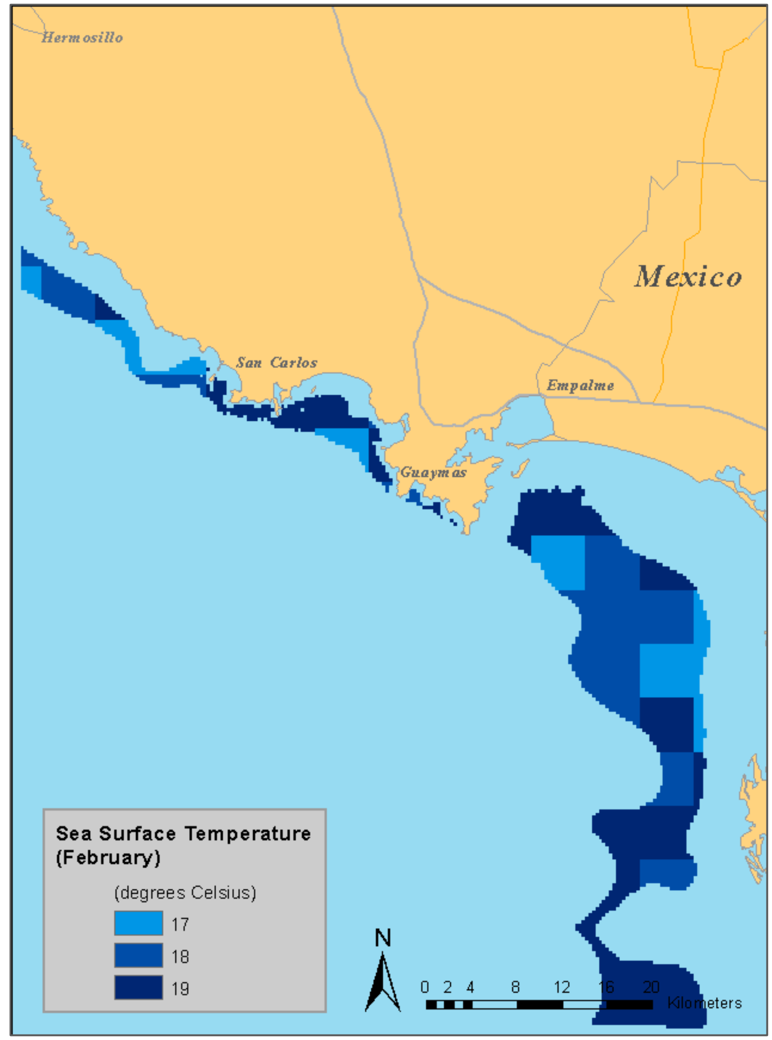

Appendix C16. Distance to Shipping Lanes—Guaymas



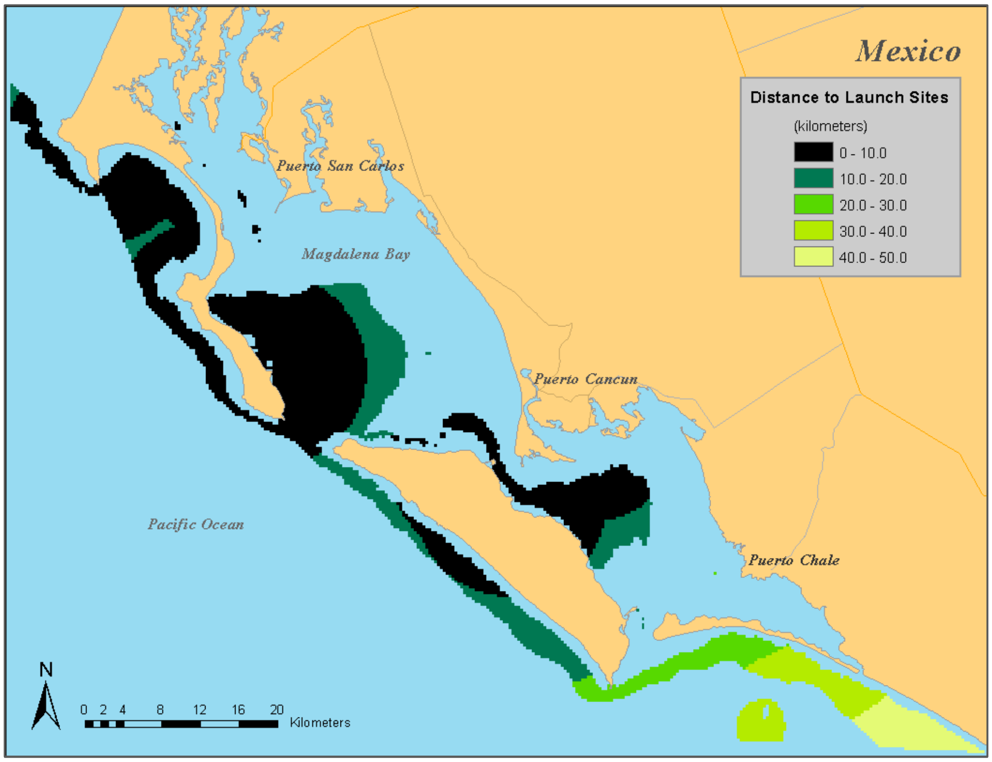
Appendix C17. SST August (warm)—Guaymas



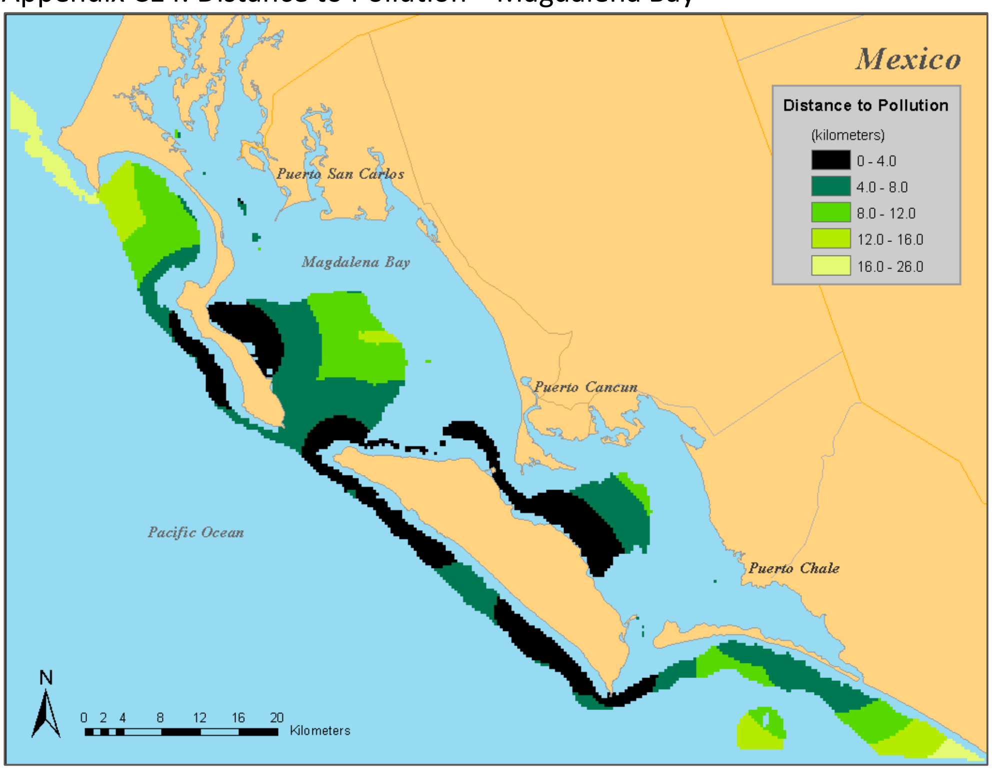

Appendix C18. SST February (cold)—Guaymas



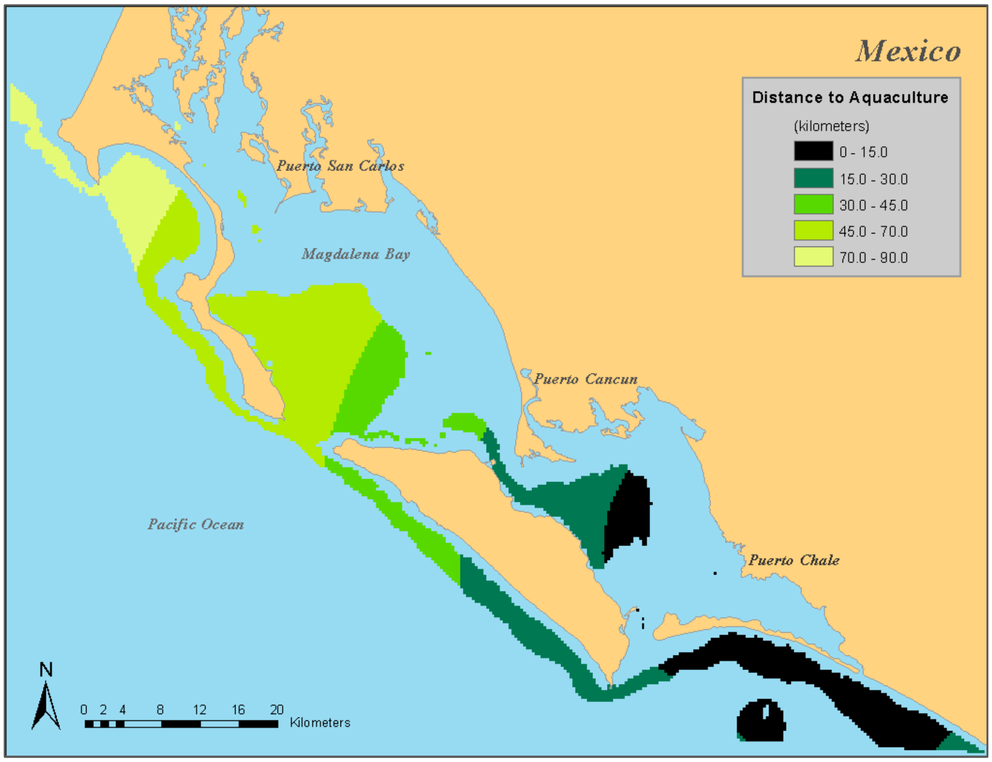
Appendix C13. Distance to Launch Sites—Magdalena Bay



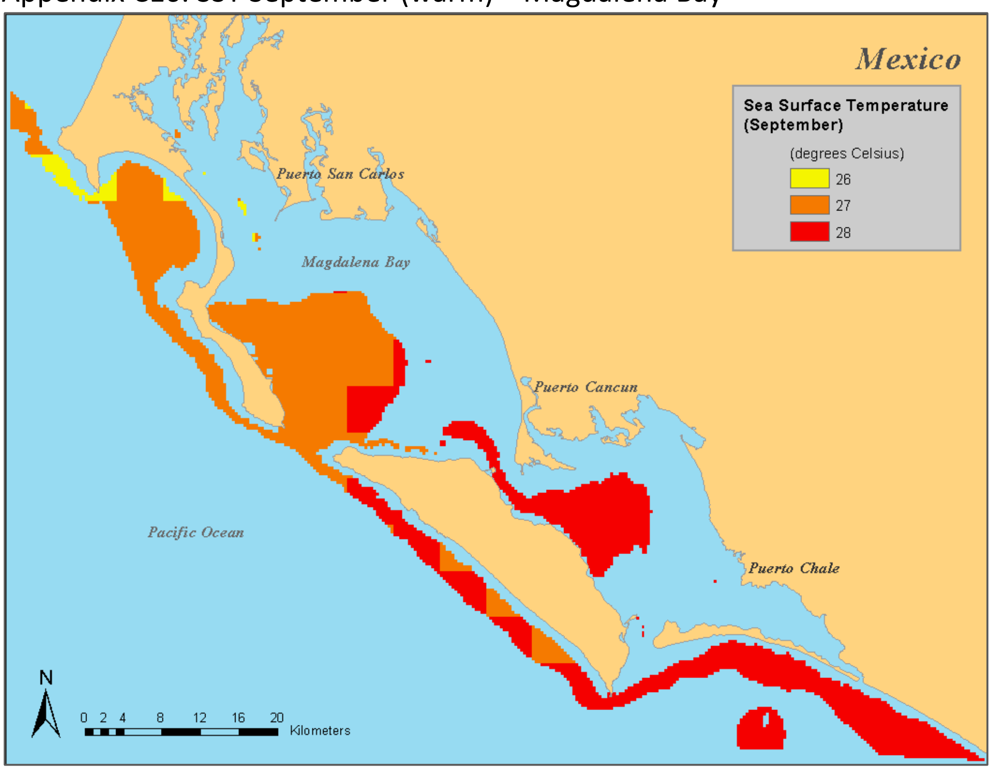

Appendix C14. Distance to Pollution—Magdalena Bay



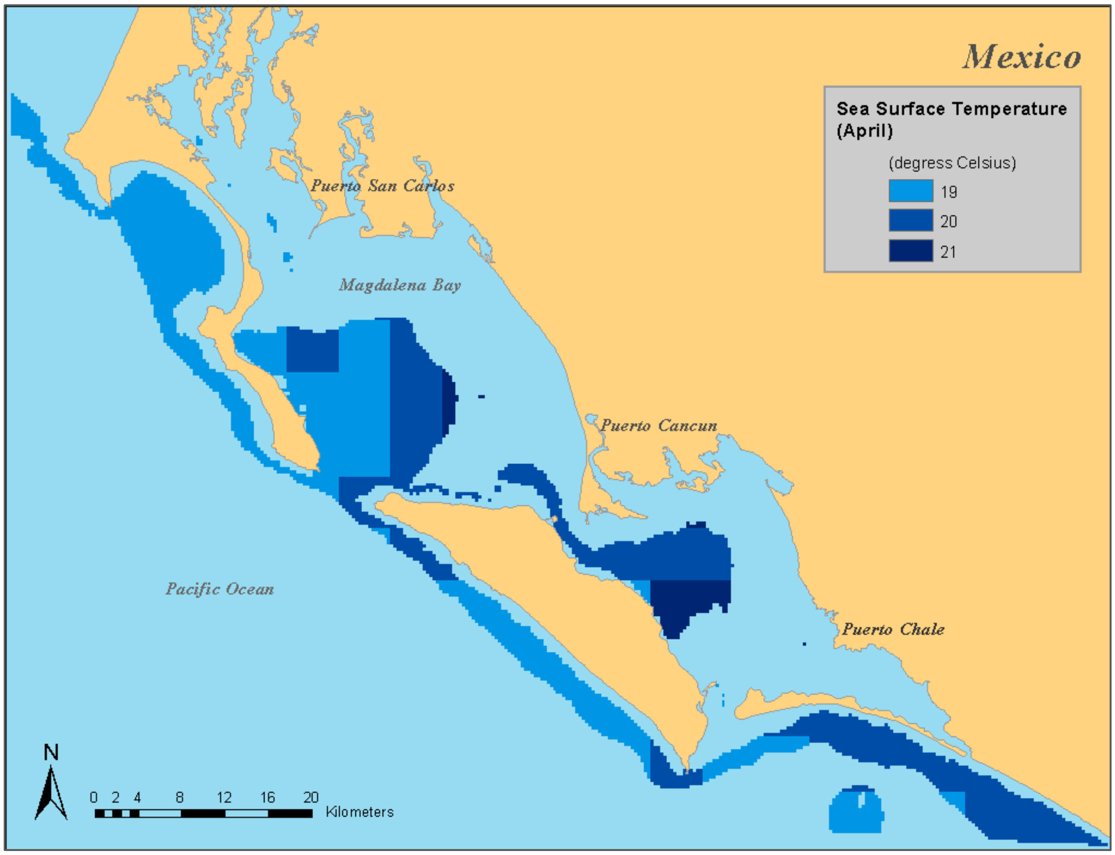
Appendix C15. Distance to Aquaculture—Magdalena Bay




Appendix C16. SST September (warm)—Magdalena Bay



Appendix C17. SST April (cold)—Magdalena Bay



## D. Spatial Input Tables

This table is an excerpt of one of the data tables used to export spatial data from GIS for use in the MATLAB spatial-bio-economic model. Each cell is represented by a row ID and unique set of geographic coordinates. The parameter attributes for each cell are associated with those unique geographic coordinates

| Rowid | X | Y | Depth (m) | Distance to Pollution (m) | Distance to Shrimp Aquaculture (m) | Distance to Launch Sites (m) | Distance to Shipping Lanes (m) |
|---|---|---|---|---|---|---|---|
| 1 | -75802.80544 | 2765368.368 | 17.28919 | 20402.21 | 10057.83 | 10057.83 | 32000.31 |
| 2 | -75502.80544 | 2765368.368 | 19.33579 | 20408.82 | 9972.462 | 9972.462 | 31767.44 |
| 3 | -75202.80544 | 2765368.368 | 21.46985 | 20419.84 | 9895.453 | 9895.453 | 31535.69 |
| 4 | -74902.80544 | 2765368.368 | 23.69325 | 20435.26 | 9827.004 | 9827.004 | 31305.11 |
| 5 | -74602.80544 | 2765368.368 | 26.00768 | 20455.07 | 9767.292 | 9767.292 | 31075.71 |
| 6 | -74302.80544 | 2765368.368 | 28.41473 | 20479.26 | 9716.48 | 9716.48 | 30847.53 |
| 7 | -74002.80544 | 2765368.368 | 30.91581 | 20507.8 | 9674.709 | 9674.709 | 30620.58 |
| 8 | -73702.80544 | 2765368.368 | 33.51217 | 20540.69 | 9642.095 | 9642.095 | 30394.9 |
| 9 | -73402.80544 | 2765368.368 | 36.20492 | 20577.9 | 9618.731 | 9618.731 | 30170.52 |
| 10 | -73102.80544 | 2765368.368 | 20619.41 | 9604.687 | 9604.687 | 29947.45 | 38.99497 |

(table continued)

| Rowid | SST Jan | SST Feb | SST Mar | SST Apr | SST May | SST Jun | SST Jul | SST Aug | SST Sep | SST Oct | SST Nov | SST Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20.925 | 20.1 | 20.175 | 21.825 | 23.475 | 25.65 | 25.95 | 28.8 | 30.45 | 29.25 | 25.95 | 22.575 |
| 2 | 20.925 | 20.1 | 20.175 | 21.825 | 23.475 | 25.65 | 25.95 | 28.8 | 30.45 | 29.25 | 25.95 | 22.575 |
| 3 | 20.925 | 20.1 | 20.175 | 21.825 | 23.475 | 25.65 | 25.95 | 28.8 | 30.45 | 29.25 | 25.95 | 22.575 |
| 4 | 20.925 | 20.1 | 20.175 | 21.825 | 23.475 | 25.65 | 25.95 | 28.8 | 30.45 | 29.25 | 25.95 | 22.575 |
| 5 | 20.925 | 20.1 | 20.175 | 21.825 | 23.475 | 25.65 | 25.95 | 28.8 | 30.45 | 29.25 | 25.95 | 22.575 |
| 6 | 20.925 | 20.175 | 20.175 | 21.9 | 23.475 | 25.35 | 27.375 | 28.8 | 29.7 | 28.2 | 25.125 | 22.575 |
| 7 | 20.175 | 20.175 | 19.425 | 21.9 | 22.875 | 25.35 | 27.375 | 28.95 | 29.7 | 28.2 | 25.125 | 22.575 |
| 8 | 20.175 | 20.175 | 19.425 | 21.9 | 22.875 | 25.35 | 27.375 | 28.95 | 29.7 | 28.2 | 25.125 | 22.575 |
| 9 | 20.175 | 20.175 | 19.425 | 21.9 | 22.875 | 25.35 | 27.375 | 28.95 | 29.7 | 28.2 | 25.125 | 22.575 |
| 10 | 20.175 | 20.175 | 19.425 | 21.9 | 22.875 | 25.35 | 27.375 | 28.95 | 29.7 | 28.2 | 25.125 | 22.575 |

## E. Spatial Bio-Economic Model MATLAB Code

### La Paz Artisanal Business Model

The following MATLAB code evaluates the net present value (NPV) of Micropods in a nine pod array in every suitable 300x300m site within the Bay of La Paz. It also includes code to produce a histogram of NPV for one location within the Bay. This code can be input directly into MATLAB and updated with new data to evaluate the economic viability of Micropod operations in other locations around the world.

```
%% Monte carlo Bio-Spatial Economic analysis of Aquapods
%
%% General Model Params
close all
clear all
load LaPazSpatial
load shrimppriceranges
tic
pause on
t=140;             %made this a constant
harv=2;            %number of harvests per year
discount=.05;
tolerance=1e-3;
time=20;            %time in years for NPV
np=9;
Shrimp_time=t/7;    %time in weeks for shrimp model
Shrimp_tseries=1:Shrimp_time+1; % The time series that the shrimp
model will work for

    w0=.012;
    Vp=212;
%% Monte Carlo Setup
delta_allprofs=1000;
sim=1000;
running_allNPV=NaN(1,sim);
store_MNPV=NaN(1,sim);
% MC_NPV=NaN(length(LaPazSpatial),sim);
it=0;
mean_NPV=1;

%
%% Non-Monte-Carlo variables

% Inputting Spatial Temperature Data
for i=1:length(LaPazSpatial) %Bring in temperature data
    Jan(i)=LaPazSpatial(i,9);
    Feb(i)=LaPazSpatial(i,10); %No harvesting
    Mar(i)=LaPazSpatial(i,11); %No harvesting
    Apr(i)=LaPazSpatial(i,12);
    May(i)=LaPazSpatial(i,13);
    Jun(i)=LaPazSpatial(i,14);
```

```
    Jul(i)=LaPazSpatial(i,15);
    Aug(i)=LaPazSpatial(i,16);
    Sep(i)=LaPazSpatial(i,17);
    Oct(i)=LaPazSpatial(i,18);
    Nov(i)=LaPazSpatial(i,19);
    Dec(i)=LaPazSpatial(i,20);
end

for i=1:length(LaPazSpatial)
    for  j=Shrimp_tseries(1:end-1)
        if j>0 && j<=4; %Temperature and Harvest for Spring
            TEMP(i,j)=Apr(i);
        elseif j > 4 && j<=8;
            TEMP(i,j)=May(i);
        elseif j >8 && j<=12;
            TEMP(i,j)=Jun(i);
        elseif j >12 && j<=16;
            TEMP(i,j)=Jul(i);
        elseif j>16 && j<= 20;
            TEMP(i,j)=Aug(i);
        elseif j >20;
            TEMP(i,j)=Sep(i);
        end
    end
end

for i=1:length(LaPazSpatial);
    for  j=Shrimp_tseries(1:end-1) ;

        Gr_sm(i,j)=-0.000104548229548085*TEMP(i,j)^4 +
0.00678128815628209*TEMP(i,j)^3 - 0.139069749694711*TEMP(i,j)^2 +
1.20503067765702*TEMP(i,j) - 4.87885989012892;
        Gr_med(i,j)=-0.000192498473748609*TEMP(i,j)^4 +
0.0163161248473876*TEMP(i,j)^3 - 0.501469971001686*TEMP(i,j)^2 +
6.71615396063011*TEMP(i,j) - 33.3332520604835;
        Gr_lg(i,j)=-0.0000672313797313931*TEMP(i,j)^4 +
0.00557547313797499*TEMP(i,j)^3 - 0.169902396214982*TEMP(i,j)^2 +
2.30515956959863*TEMP(i,j) - 11.8629876373727;
    end
end
avg_weight=NaN(length(LaPazSpatial),length(Shrimp_tseries)-1);
for i=1:length(LaPazSpatial);
    for  j=Shrimp_tseries(1:end-2) ;
        avg_weight(:,1)=w0;
        if avg_weight(i,j)<=10.8 && Gr_sm(i,j)>0;
            avg_weight(i, j+1)=avg_weight(i, j)+ Gr_sm(i,j);
        elseif avg_weight(i, j)<=10.8 && Gr_sm(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j+1)+ 0;
        end
        if avg_weight(i, j)>10.8 && avg_weight(i, j)<16 &&
Gr_med(i,j)>0;
            avg_weight(i, j+1)=avg_weight(i, j)+ Gr_med(i,j);
```

```
        elseif avg_weight(i, j)>10.8 && avg_weight(i, j)<16 &&
Gr_med(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j+1)+ 0;
        end
        if avg_weight(i, j)>=16 && Gr_lg(i,j)>0;
            avg_weight(i,j+1)=avg_weight(i, j)+ Gr_lg(i,j);
        elseif avg_weight(i, j)>=16 && Gr_lg(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j)+ 0;
        end
    end
end
for i=1:length(LaPazSpatial);
    finalweight(i)=avg_weight(i,end); % i all the rows, 20-column 20
end
%%Round 2 Growth
for i=1:length(LaPazSpatial)
    for  j=Shrimp_tseries(1:end-1)
        if j>0 && j<=4; %Temperature and Harvest for Fall
            TEMP2(i,j)=Sep(i);
        elseif j > 4 && j<=8;
            TEMP2(i,j)=Oct(i);
        elseif j >8 && j<=12;
            TEMP2(i,j)=Nov(i);
        elseif j >12 && j<= 16;
            TEMP2(i,j)=Dec(i);
        elseif j>16 && j<= 20;
            TEMP2(i,j)=Jan(i);
        elseif j >20;
            TEMP2(i,j)=Feb(i);
        end
    end
end
for i=1:length(LaPazSpatial);
    for  j=Shrimp_tseries(1:end-1) ;

        Gr_sm2(i,j)=-0.000104548229548085*TEMP2(i,j)^4 +
0.00678128815628209*TEMP2(i,j)^3 - 0.139069749694711*TEMP2(i,j)^2 +
1.20503067765702*TEMP2(i,j) - 4.87885989012892;
        Gr_med2(i,j)=-0.000192498473748609*TEMP2(i,j)^4 +
0.0163161248473876*TEMP2(i,j)^3 - 0.501469971001686*TEMP2(i,j)^2 +
6.71615396063011*TEMP2(i,j) - 33.3332520604835;
        Gr_lg2(i,j)=-0.0000672313797313931*TEMP2(i,j)^4 +
0.00557547313797499*TEMP2(i,j)^3 - 0.169902396214982*TEMP2(i,j)^2 +
2.30515956959863*TEMP2(i,j) - 11.8629876373727;
    end
end
avg_weight2=NaN(length(LaPazSpatial),length(Shrimp_tseries)-1);
for i=1:length(LaPazSpatial);
    for  j=Shrimp_tseries(1:end-2) ;
        avg_weight2(:,1)=w0;
        if avg_weight2(i,j)<=10.8 && Gr_sm2(i,j)>0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ Gr_sm2(i,j);
        elseif avg_weight2(i, j)<=10.8 && Gr_sm2(i,j)<0;
```

```
            avg_weight2(i, j+1)=avg_weight2(i, j+1)+ 0;
        end
        if avg_weight2(i, j)>10.8 && avg_weight2(i, j)<16 &&
Gr_med2(i,j)>0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ Gr_med2(i,j);
        elseif avg_weight2(i, j)>10.8 && avg_weight2(i, j)<16 &&
Gr_med2(i,j)<0;
            avg_weight2(i, j+1)=avg_weight2(i, j+1)+ 0;
        end
        if avg_weight2(i, j)>=16 && Gr_lg2(i,j)>0;
            avg_weight2(i,j+1)=avg_weight2(i, j)+ Gr_lg2(i,j);
        elseif avg_weight2(i, j)>=16 && Gr_lg2(i,j)<0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ 0;
        end
    end
end

for i=1:length(LaPazSpatial);
    finalweight2(i)=avg_weight2(i,end); % i all the rows, 20-column
20
end


for i=1:sim
    it=it+1

    %Monte Carlo Variables
    pfu=.5+(1-.5)*rand;
    fec1=.4+(.8-.4)*rand;
    fec2=2+(4-2)*rand;
    dv=6+(8-6)*rand;
    dw=5+(12-5)*rand;
    pf=.6+(1.8-.6)*rand;
    Cc=500+(2000-500)*rand;
    a=12+(18-12)*rand;
    pfdg=800+(2000-800)*rand;
    pvdg=.6+(1-.6)*rand;
    ppl=.005+(.02-.005)*rand;
    d=200+(600-200)*rand;
    wi=.005+(.019-.005)*rand;
    mpsa=(22.93+(23.15-22.93)*rand)*.7;
    mpsb=(20.17+(20.39-20.17)*rand)*.7;
    mpsc=(19.51+(19.73-19.51)*rand)*.7;
    mpsd=(16.2+(16.42-16.2)*rand)*.7;
    mpse=(13.45+(13.67-13.45)*rand)*.7;
    mpsf=(12.35+(12.57-12.35)*rand)*.7;
    mpsg=(10.03+(10.25-10.03)*rand)*.7;
    mpsh=(8.05+(8.27-8.05)*rand)*.7;
    mpsi=(7.72+(7.94-7.72)*rand)*.7;
    mpsj=(7.05+(7.28-7.05)*rand)*.7;
    mpsk=(6.39+(6.61-6.39)*rand)*.7;
    mpsl=(5.18+(5.40-5.18)*rand)*.7;
    rbaq=0+(.1-0)*rand;
```

```
    z=.001+(.01-.001)*rand;

    Sh_pr=[mpsa mpsb mpsc mpsd mpse mpsf mpsg mpsh mpsi mpsj mpsk
mpsl];

    pfu_MC(it)=pfu; %Storing fuel price per model iteration
    z_MC(it)=z; %Storing int. mortality rate per model iteration
    pf_MC(it)=pf; %Storing price of feed per model iteration
    dw_MC(it)=dw; %Storing dive wage per model iteration
    d_MC(it)=d; %Storing stocking density per model iteration

    %% Shrimp Growth and Revenue

    No=Vp*d;
    NS=No*exp(-z*Shrimp_tseries); %Number of shrimp in each week,
starting in week 0

    %chops off extra week
    NS=NS(1:end-1);

    NSmat=repmat(NS,length(LaPazSpatial),1);%turns NS into a
compatible matrix with average weight
    Sh_Biomass=avg_weight.*NSmat./1000; %in kilograms
    Sh_Biomass2=avg_weight2.*NSmat./1000;

    %% Feed Model

    feed=NaN(length(LaPazSpatial),length(Shrimp_tseries)-1);

    for i=1:length(LaPazSpatial);

        for  j=Shrimp_tseries(1:end-1) ;

            if avg_weight(i,j)<=10.8;
                feed(i,j)=(-0.025*TEMP(i,j)^2 + 1.675*TEMP(i,j)-
19)*.01*Sh_Biomass(i,j)*7; %.01 to make percentage correct*7
days*biomass in kg
            elseif avg_weight(i,j)<16;
                feed(i,j)=(-0.0095*TEMP(i,j)^2 + 0.7762*TEMP(i,j)-
9.6143)*.01*Sh_Biomass(i,j)*7;
            elseif avg_weight(i,j)>=16;
                feed(i,j)=(4e-16*TEMP(i,j)^2 + 0.2*TEMP(i,j)-
2.5)*.01*Sh_Biomass(i,j)*7;
            end

        end
    end

    Totalfeed=sum(feed,2)*np;
    Totalfeed_MC(:,it)=Totalfeed; %Storing totalfeed per model
iteration
```

```
 %% Feed Model Harvest 2
feed2=NaN(length(LaPazSpatial),length(Shrimp_tseries)-1);

for i=1:length(LaPazSpatial);

    for  j=Shrimp_tseries(1:end-1) ;

        if avg_weight2(i,j)<=10.8;
            feed2(i,j)=(-0.025*TEMP2(i,j)^2 + 1.675*TEMP2(i,j)-
19)*.01*Sh_Biomass2(i,j)*7; %.01 to make percentage correct*7
days*biomass in kg
        elseif avg_weight2(i,j)<16;
            feed2(i,j)=(-0.0095*TEMP2(i,j)^2 +
0.7762*TEMP2(i,j)-9.6143)*.01*Sh_Biomass2(i,j)*7;
        elseif avg_weight2(i,j)>=16;
            feed2(i,j)=(4e-16*TEMP2(i,j)^2 + 0.2*TEMP2(i,j)-
2.5)*.01*Sh_Biomass2(i,j)*7;
        end

    end
end

Totalfeed2=sum(feed2,2)*np;
Totalfeed2_MC(:, it)=Totalfeed2;

%%pricing the Shrimp Harvest 1
pr=NaN(length(LaPazSpatial),1);
for i=1:length(finalweight);
    if finalweight(i)>=45
        pr(i)=Sh_pr(1)';
    elseif  finalweight(i)>=38
        pr(i)=Sh_pr(2');
    elseif  finalweight(i)>=30
        pr(i)=Sh_pr(3)';
    elseif  finalweight(i)>=23
        pr(i)=Sh_pr(4)';
    elseif finalweight(i)>=18
        pr(i)=Sh_pr(5)';
    elseif  finalweight(i)>=15
        pr(i)=Sh_pr(6)';
    elseif  finalweight(i)>=11
        pr(i)=Sh_pr(7)';
    elseif  finalweight(i)>=9
        pr(i)=Sh_pr(8)';
    elseif  finalweight(i)>=8
        pr(i)=Sh_pr(9)';
    elseif  finalweight(i)>=7
        pr(i)=Sh_pr(10)';
    elseif  finalweight(i)>=6
        pr(i)=Sh_pr(11)';
    elseif finalweight(i)<6
```

```
            pr(i)=Sh_pr(12)';
        end
    end

        %%pricing the Shrimp Harvest 2
    pr2=NaN(length(LaPazSpatial),1);
    for i=1:length(finalweight2);
        if finalweight2(i)>=45
            pr2(i)=Sh_pr(1)';
        elseif  finalweight2(i)>=38
            pr2(i)=Sh_pr(2');
        elseif  finalweight2(i)>=30
            pr2(i)=Sh_pr(3)';
        elseif  finalweight2(i)>=23
            pr2(i)=Sh_pr(4)';
        elseif finalweight2(i)>=18
            pr2(i)=Sh_pr(5)';
        elseif  finalweight2(i)>=15
            pr2(i)=Sh_pr(6)';
        elseif  finalweight2(i)>=11
            pr2(i)=Sh_pr(7)';
        elseif  finalweight2(i)>=9
            pr2(i)=Sh_pr(8)';
        elseif  finalweight2(i)>=8
            pr2(i)=Sh_pr(9)';
        elseif  finalweight2(i)>=7
            pr2(i)=Sh_pr(10)';
        elseif  finalweight2(i)>=6
            pr2(i)=Sh_pr(11)';
        elseif finalweight2(i)<6
            pr2(i)=Sh_pr(12)';
        end
    end
             R=NaN(length(LaPazSpatial),1);
        for i=1:length(LaPazSpatial);

            R(i)=(pr(i)+ rbaq*pr(i)).*Sh_Biomass(i,end)*np;% 2 for 2
harvests/year, np for the number of pods, revenue bonus, biomass no
heads
        end
          R2=NaN(length(LaPazSpatial),1);
        for i=1:length(LaPazSpatial);

            R2(i)=(pr2(i)+ rbaq*pr(i)).*Sh_Biomass2(i,end)*np;% 2
for 2 harvests/year, np for the number of pods, revenue bonus,
biomass no heads
        end
        pr_MC(:,it)=pr;

        %% Costs
        paq= 21625;
        Cb= 40000;
        rsl=.01;        %these are the probabilities of risk
```

```
        xslh=1.5;
        pa= 4;
        rsd= .02;
        dph= 30;
        rd=.3;
        xaqh=1;
        rps=.2;
        xpsh=1;

        for y=1:2 %year one, year 2+
            for i=1:length(LaPazSpatial) %Bring in spatial risk data
                if y>1 %for costs after year 1
                    % variables that change in time
                    Cb=0;
                    paq=0;
                    pi=0;
                    Cc=100;
                    pfdg=0; %fixed gear dive costs zero after year 1
                end

                dp(i)=LaPazSpatial(i,4); %Depth - distance in meters
                xaq(i)=LaPazSpatial(i,5); %Aquaculture
                xps(i)=LaPazSpatial(i,6); %Pollution
                xt(i)=LaPazSpatial(i,7);  %Launch Site
                xsl(i)=LaPazSpatial(i,8); %Shipping Lane

                ECSL(i)=rsl*2^(-
xsl(i)/1000/xslh)*(paq+t/365*(R(i)/np)); %****Have to fix, for
average revenue in a year b/c revenues will be different based on
harvests*
                ECSL2(i)=rsl*2^(-
xsl(i)/1000/xslh)*(paq+t/365*(R2(i)/np));
                ECSD(i)=rsd*2^(-dp(i)/dph)*(paq*np+t/365*(R(i)));
                ECSD2(i)=rsd*2^(-dp(i)/dph)*(paq*np+t/365*(R2(i)));

                ECD(i)=rd*2^(-xaq(i)/1000/xaqh)*(R(i));
                ECD2(i)=rd*2^(-xaq(i)/1000/xaqh)*(R2(i));
                EPS(i)=rps*2^(-xps(i)/1000/xpsh)*(.2*R(i));
                EPS2(i)=rps*2^(-xps(i)/1000/xpsh)*(.2*R2(i));

                dh(i)=6+(xt(i)/1000/15)*2; %make this a function of
distance, not in monte carlo

                CLabor=(dv*dh(i)*dw*355); %355 Day work year!
                CStocking=(ppl*d*Vp*np*harv);
                CDivefixed=(pfdg*dv);
                CDivevar=(pvdg*dv*355);
                CAir=(pa*a*355);
                CTravel=(2*xt(i)/1000*(fec1+fec2)*pfu*355); %Divided
by 1000 because input data was in meters
                CFeed=(Totalfeed(i)*pf)+(Totalfeed2(i)*pf);
                CConcession=Cc;
```

```
                CAquapod=(paq*np);
                CInstall=(pi*np);
                CBoat=Cb;

C(i,y)=CLabor+CStocking+CDivefixed+CDivevar+CAir+CTravel+CFeed+CConc
ession+CAquapod+CInstall+CBoat+ECSL(i)+ECSD(i)+ECD(i)+EPS(i)+ECSL2(i
)+ECSD2(i)+ECD2(i)+EPS2(i); %Costs for one harvest operation (change
by changing to 2*t or *360 - get 5 days off

            end
        end

 MC_CLabor(it)=CLabor;
 MC_CTravel(it)=CTravel;
 MC_CAir(it)=CAir;
 MC_CStocking(it)=CStocking;
 MC_Cc(it)=Cc;
 MC_CDivefixed(it)=CDivefixed;
 MC_CDivevar(it)=CDivevar;
 MC_CFeed(it)=CFeed;

        %% Final Profits

        prof1=R+R2-C(:,1);

        prof2=R+R2-C(:,2);

        profits=[prof1 prof2*ones(1,19)];

        %% NPV Calculations
        NPVtseries=1:time;%Array for each year of in our business
model

        Discountfactor=NaN(1,length(NPVtseries));
        for i=NPVtseries
            Discountfactor(i)=1/(1+discount).^(i-1);  %Discount
factor each year's profit will be multiplied by
        end

        Discountfactor=repmat(Discountfactor,length(profits),1);
        Discprofits=profits.*Discountfactor;

        NPV=sum(Discprofits,2) ;      %NPV

        NPV_MC(:,it)=NPV; %store monte carlo NPV results in each
patch FINAL RESULTS HERE
        [toc i]

    sorted_MC=sort(NPV_MC,2);
end
```

```
E_NPV=mean(NPV_MC,2); %calculates expected NPV at each location,
this is the column we EXPORT TO GIS!!!!!

sorted_ENPV=sort(E_NPV,1);

%%Histograms

sorted_MC=sort(NPV_MC,2); %sorts each patch from low to high
hist(sorted_MC(1,1:1000),75); %histogram of one patch-this is what
we use to show the level of uncertainty
xlabel('NPV');
ylabel('Frequency');
```

**La Paz Industrial Business Model**

The following MATLAB code evaluates the net present value (NPV) of industrial-scale Aquapod operations in each potential 700x700 meter site within the industrially suitable area in La Paz. This code can be updated with new data to examine the economic viability of large-scale Aquapod operations in other locations around the world.

```
%% Monte carlo Bio-Spatial Economic analysis of Aquapods
%
%% General Model Params
close all
clear all
load LaPazIndustrial
load shrimppriceranges

tic
pause on
t=140;              %made this a constant
harv=2;             %number of harvests per year
discount=.05;
tolerance=1e-3;
time=20;             %time in years for NPV
np=16;
Shrimp_time=t/7;     %time in weeks for shrimp model
Shrimp_tseries=1:Shrimp_time+1; % The time series that the shrimp
model will work for
    w0=.012;
    Vp=7000;
%% Monte Carlo Setup

delta_allprofs=1000;
sim=10000;
running_allNPV=NaN(1,sim);
store_MNPV=NaN(1,sim);
% MC_NPV=NaN(length(LaPazIndustrial),sim);
it=0;
```

```
mean_NPV=1;
%
%% Non-Monte-Carlo variables

% Inputting Spatial Temperature Data
for i=1:length(LaPazIndustrial) %Bring in temperature data
    Jan(i)=LaPazIndustrial(i,9);
    Feb(i)=LaPazIndustrial(i,10); %No harvesting
    Mar(i)=LaPazIndustrial(i,11); %No harvesting
    Apr(i)=LaPazIndustrial(i,12);
    May(i)=LaPazIndustrial(i,13);
    Jun(i)=LaPazIndustrial(i,14);
    Jul(i)=LaPazIndustrial(i,15);
    Aug(i)=LaPazIndustrial(i,16);
    Sep(i)=LaPazIndustrial(i,17);
    Oct(i)=LaPazIndustrial(i,18);
    Nov(i)=LaPazIndustrial(i,19);
    Dec(i)=LaPazIndustrial(i,20);
end
for i=1:length(LaPazIndustrial)
    for  j=Shrimp_tseries(1:end-1)
        if j>0 && j<=4; %Temperature and Harvest for Spring
            TEMP(i,j)=Apr(i);
        elseif j > 4 && j<=8;
            TEMP(i,j)=May(i);
        elseif j >8 && j<=12;
            TEMP(i,j)=Jun(i);
        elseif j >12 && j<=16;
            TEMP(i,j)=Jul(i);
        elseif j>16 && j<= 20;
            TEMP(i,j)=Aug(i);
        elseif j >20;
            TEMP(i,j)=Sep(i);
        end
    end
end
for i=1:length(LaPazIndustrial);
    for  j=Shrimp_tseries(1:end-1) ;

        Gr_sm(i,j)=-0.000104548229548085*TEMP(i,j)^4 +
0.00678128815628209*TEMP(i,j)^3 - 0.139069749694711*TEMP(i,j)^2 +
1.20503067765702*TEMP(i,j) - 4.87885989012892;
        Gr_med(i,j)=-0.000192498473748609*TEMP(i,j)^4 +
0.0163161248473876*TEMP(i,j)^3 - 0.501469971001686*TEMP(i,j)^2 +
6.71615396063011*TEMP(i,j) - 33.3332520604835;
        Gr_lg(i,j)=-0.0000672313797313931*TEMP(i,j)^4 +
0.00557547313797499*TEMP(i,j)^3 - 0.169902396214982*TEMP(i,j)^2 +
2.30515956959863*TEMP(i,j) - 11.8629876373727;
    end
end
avg_weight=NaN(length(LaPazIndustrial),length(Shrimp_tseries)-1);
for i=1:length(LaPazIndustrial);
    for  j=Shrimp_tseries(1:end-2) ;
```

```
        avg_weight(:,1)=w0;
        if avg_weight(i,j)<=10.8 && Gr_sm(i,j)>0;
            avg_weight(i, j+1)=avg_weight(i, j)+ Gr_sm(i,j);
        elseif avg_weight(i, j)<=10.8 && Gr_sm(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j+1)+ 0;
        end
        if avg_weight(i, j)>10.8 && avg_weight(i, j)<16 &&
Gr_med(i,j)>0;
            avg_weight(i, j+1)=avg_weight(i, j)+ Gr_med(i,j);
        elseif avg_weight(i, j)>10.8 && avg_weight(i, j)<16 &&
Gr_med(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j+1)+ 0;
        end

        if avg_weight(i, j)>=16 && Gr_lg(i,j)>0;
            avg_weight(i,j+1)=avg_weight(i, j)+ Gr_lg(i,j);
        elseif avg_weight(i, j)>=16 && Gr_lg(i,j)<0;
            avg_weight(i, j+1)=avg_weight(i, j)+ 0;
        end
    end
end

for i=1:length(LaPazIndustrial);
    finalweight(i)=avg_weight(i,end); % i all the rows, 20-column 20
end
%%Round 2 Growth

for i=1:length(LaPazIndustrial)
    for  j=Shrimp_tseries(1:end-1)
        if j>0 && j<=4; %Temperature and Harvest for Fall
            TEMP2(i,j)=Sep(i);
        elseif j > 4 && j<=8;
            TEMP2(i,j)=Oct(i);
        elseif j >8 && j<=12;
            TEMP2(i,j)=Nov(i);
        elseif j >12 && j<= 16;
            TEMP2(i,j)=Dec(i);
        elseif j>16 && j<= 20;
            TEMP2(i,j)=Jan(i);
        elseif j >20;
            TEMP2(i,j)=Feb(i);
        end
    end
end

for i=1:length(LaPazIndustrial);
    for  j=Shrimp_tseries(1:end-1) ;

        Gr_sm2(i,j)=-0.000104548229548085*TEMP2(i,j)^4 +
0.00678128815628209*TEMP2(i,j)^3 - 0.139069749694711*TEMP2(i,j)^2 +
1.20503067765702*TEMP2(i,j) - 4.87885989012892;
```

```
        Gr_med2(i,j)=-0.000192498473748609*TEMP2(i,j)^4 +
0.0163161248473876*TEMP2(i,j)^3 - 0.501469971001686*TEMP2(i,j)^2 +
6.71615396063011*TEMP2(i,j) - 33.3332520604835;
        Gr_lg2(i,j)=-0.0000672313797313931*TEMP2(i,j)^4 +
0.00557547313797499*TEMP2(i,j)^3 - 0.169902396214982*TEMP2(i,j)^2 +
2.30515956959863*TEMP2(i,j) - 11.8629876373727;
    end
end

avg_weight2=NaN(length(LaPazIndustrial),length(Shrimp_tseries)-1);

for i=1:length(LaPazIndustrial);
    for  j=Shrimp_tseries(1:end-2) ;

        avg_weight2(:,1)=w0;

        if avg_weight2(i,j)<=10.8 && Gr_sm2(i,j)>0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ Gr_sm2(i,j);
        elseif avg_weight2(i, j)<=10.8 && Gr_sm2(i,j)<0;
            avg_weight2(i, j+1)=avg_weight2(i, j+1)+ 0;
        end

        if avg_weight2(i, j)>10.8 && avg_weight2(i, j)<16 &&
Gr_med2(i,j)>0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ Gr_med2(i,j);
        elseif avg_weight2(i, j)>10.8 && avg_weight2(i, j)<16 &&
Gr_med2(i,j)<0;
            avg_weight2(i, j+1)=avg_weight2(i, j+1)+ 0;
        end

        if avg_weight2(i, j)>=16 && Gr_lg2(i,j)>0;
            avg_weight2(i,j+1)=avg_weight2(i, j)+ Gr_lg2(i,j);
        elseif avg_weight2(i, j)>=16 && Gr_lg2(i,j)<0;
            avg_weight2(i, j+1)=avg_weight2(i, j)+ 0;
        end

    end



end

for i=1:length(LaPazIndustrial);
    finalweight2(i)=avg_weight2(i,end); % i all the rows, 20-column
20
end

for i=1:sim
    it=it+1

    %Monte Carlo Variables
    pfu=.5+(1-.5)*rand;
```

```
    fec1=.4+(.8-.4)*rand;
    fec2=2+(4-2)*rand;
    dw=5+(12-5)*rand;
    pf=.6+(1.8-.6)*rand;
    Cc=500+(2000-500)*rand;
    a=12+(18-12)*rand;
    pfdg=800+(2000-800)*rand;
    pvdg=.6+(1-.6)*rand;
    ppl=.005+(.02-.005)*rand;
    d=200+(600-200)*rand;
    mpsa=(22.93+(23.15-22.93)*rand)*.7;
    mpsb=(20.17+(20.39-20.17)*rand)*.7;
    mpsc=(19.51+(19.73-19.51)*rand)*.7;
    mpsd=(16.2+(16.42-16.2)*rand)*.7;
    mpse=(13.45+(13.67-13.45)*rand)*.7;
    mpsf=(12.35+(12.57-12.35)*rand)*.7;
    mpsg=(10.03+(10.25-10.03)*rand)*.7;
    mpsh=(8.05+(8.27-8.05)*rand)*.7;
    mpsi=(7.72+(7.94-7.72)*rand)*.7;
    mpsj=(7.05+(7.28-7.05)*rand)*.7;
    mpsk=(6.39+(6.61-6.39)*rand)*.7;
    mpsl=(5.18+(5.40-5.18)*rand)*.7;
    rbaq=0+(.1-0)*rand;
    z=.001+(.01-.001)*rand;

    Sh_pr=[mpsa mpsb mpsc mpsd mpse mpsf mpsg mpsh mpsi mpsj mpsk
mpsl];

    pfu_MC(it)=pfu; %Storing fuel price per model iteration
    z_MC(it)=z; %Storing int. mortality rate per model iteration
    pf_MC(it)=pf; %Storing price of feed per model iteration
    dw_MC(it)=dw; %Storing dive wage per model iteration
    d_MC(it)=d; %Storing stocking density per model iteration

    %% Shrimp Growth and Revenue

    No=Vp*d;
    NS=No*exp(-z*Shrimp_tseries); %Number of shrimp in each week,
starting in week 0

    %chops off extra week
    NS=NS(1:end-1);

    NSmat=repmat(NS,length(LaPazIndustrial),1);%turns NS into a
compatible matrix with average weight
    Sh_Biomass=avg_weight.*NSmat./1000; %in kilograms
    Sh_Biomass2=avg_weight2.*NSmat./1000;

    %% Feed Model

    feed=NaN(length(LaPazIndustrial),length(Shrimp_tseries)-1);
```

```
    for i=1:length(LaPazIndustrial);

        for  j=Shrimp_tseries(1:end-1) ;

            if avg_weight(i,j)<=10.8;
                feed(i,j)=(-0.025*TEMP(i,j)^2 + 1.675*TEMP(i,j)-
19)*.01*Sh_Biomass(i,j)*7; %.01 to make percentage correct*7
days*biomass in kg
            elseif avg_weight(i,j)<16;
                feed(i,j)=(-0.0095*TEMP(i,j)^2 + 0.7762*TEMP(i,j)-
9.6143)*.01*Sh_Biomass(i,j)*7;
            elseif avg_weight(i,j)>=16;
                feed(i,j)=(4e-16*TEMP(i,j)^2 + 0.2*TEMP(i,j)-
2.5)*.01*Sh_Biomass(i,j)*7;
            end

        end
    end

    Totalfeed=sum(feed,2)*np;
    Totalfeed_MC(:,it)=Totalfeed; %Storing totalfeed per model
iteration

     %% Feed Model Harvest 2

    feed2=NaN(length(LaPazIndustrial),length(Shrimp_tseries)-1);

    for i=1:length(LaPazIndustrial);

        for  j=Shrimp_tseries(1:end-1) ;

            if avg_weight2(i,j)<=10.8;
                feed2(i,j)=(-0.025*TEMP2(i,j)^2 + 1.675*TEMP2(i,j)-
19)*.01*Sh_Biomass2(i,j)*7; %.01 to make percentage correct*7
days*biomass in kg
            elseif avg_weight2(i,j)<16;
                feed2(i,j)=(-0.0095*TEMP2(i,j)^2 +
0.7762*TEMP2(i,j)-9.6143)*.01*Sh_Biomass2(i,j)*7;
            elseif avg_weight2(i,j)>=16;
                feed2(i,j)=(4e-16*TEMP2(i,j)^2 + 0.2*TEMP2(i,j)-
2.5)*.01*Sh_Biomass2(i,j)*7;
            end

        end
    end

    Totalfeed2=sum(feed2,2)*np;
    Totalfeed2_MC(:, it)=Totalfeed2;

    %%pricing the Shrimp Harvest 1
    pr=NaN(length(LaPazIndustrial),1);
```

```
for i=1:length(finalweight);
    if finalweight(i)>=45
        pr(i)=Sh_pr(1)';
    elseif  finalweight(i)>=38
        pr(i)=Sh_pr(2');
    elseif  finalweight(i)>=30
        pr(i)=Sh_pr(3)';
    elseif  finalweight(i)>=23
        pr(i)=Sh_pr(4)';
    elseif finalweight(i)>=18
        pr(i)=Sh_pr(5)';
    elseif  finalweight(i)>=15
        pr(i)=Sh_pr(6)';
    elseif  finalweight(i)>=11
        pr(i)=Sh_pr(7)';
    elseif  finalweight(i)>=9
        pr(i)=Sh_pr(8)';
    elseif  finalweight(i)>=8
        pr(i)=Sh_pr(9)';
    elseif  finalweight(i)>=7
        pr(i)=Sh_pr(10)';
    elseif  finalweight(i)>=6
        pr(i)=Sh_pr(11)';
    elseif finalweight(i)<6
        pr(i)=Sh_pr(12)';
    end
end

    %%pricing the Shrimp Harvest 2
pr2=NaN(length(LaPazIndustrial),1);
for i=1:length(finalweight2);
    if finalweight2(i)>=45
        pr2(i)=Sh_pr(1)';
    elseif  finalweight2(i)>=38
        pr2(i)=Sh_pr(2');
    elseif  finalweight2(i)>=30
        pr2(i)=Sh_pr(3)';
    elseif  finalweight2(i)>=23
        pr2(i)=Sh_pr(4)';
    elseif finalweight2(i)>=18
        pr2(i)=Sh_pr(5)';
    elseif  finalweight2(i)>=15
        pr2(i)=Sh_pr(6)';
    elseif  finalweight2(i)>=11
        pr2(i)=Sh_pr(7)';
    elseif  finalweight2(i)>=9
        pr2(i)=Sh_pr(8)';
    elseif  finalweight2(i)>=8
        pr2(i)=Sh_pr(9)';
    elseif  finalweight2(i)>=7
        pr2(i)=Sh_pr(10)';
    elseif  finalweight2(i)>=6
        pr2(i)=Sh_pr(11)';
```

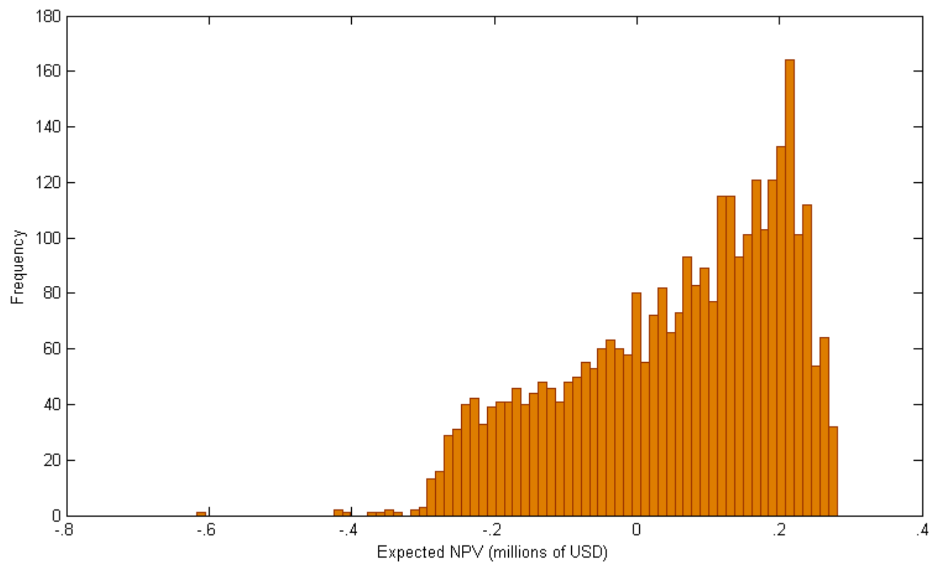
```
        elseif finalweight2(i)<6
            pr2(i)=Sh_pr(12)';
        end
    end

            R=NaN(length(LaPazIndustrial),1);
        for i=1:length(LaPazIndustrial);

            R(i)=(pr(i)+ rbaq*pr(i)).*Sh_Biomass(i,end)*np;% 2 for 2
harvests/year, np for the number of pods, revenue bonus, biomass no
heads
        end

          R2=NaN(length(LaPazIndustrial),1);
        for i=1:length(LaPazIndustrial);

            R2(i)=(pr2(i)+ rbaq*pr(i)).*Sh_Biomass2(i,end)*np;% 2
for 2 harvests/year, np for the number of pods, revenue bonus,
biomass no heads
        end

        pr_MC(:,it)=pr;

        %% Costs

        paq=300000;
        Cpanga=20000;
        Cplatform=120000;
        Ctrawler= 200000;
        Crov=50000;

        Cwarehouse=25000; % every year

        divers=16;
        mechsalary=38000;
        managersalary=56000;
        accountsalary=9000;
        watchmendaily=112;
        leaddiverwage=15;

        rsl=.01;        %these are the probabilities of risk
        xslh=1.5;
        pa= 4;
        rsd= .02;
        dph= 30;
        rd=.3;
        xaqh=1;
        rps=.2;
        xpsh=1;

        for y=1:2 %year one, year 2+
```

```
            for i=1:length(LaPazIndustrial) %Fixed costs are zero
after year 1

                if y>1 %for costs after year 1
                    %remane variables that change in time
                    Cpanga=0; % panga covered
                    Cplatform=0; %platform boat covered
                    Ctrawler=36500;% maintenance every year,
$100/day to run electicity, compressors, mobilization
                    Crov=0; %rov covered
                    paq=0; % aquapods covered
                    pi=0; %installation fee covered
                    Cc=100; % concession renewal fee
                    pfdg=0; % fixed cost dive gear covered
                end
                dp(i)=LaPazIndustrial(i,4); %Depth This is distance
in meters
                xaq(i)=LaPazIndustrial(i,5); %Aquaculture
                xps(i)=LaPazIndustrial(i,6); %Pollution
                xt(i)=LaPazIndustrial(i,7);  %Launch Site
                xsl(i)=LaPazIndustrial(i,8); %Shipping Lane

                ECSL(i)=rsl*2^(-
xsl(i)/1000/xslh)*(paq+t/365*(R(i)/np)); %****Have to fix, for
average revenue in a year b/c revenues will be different based on
harvests*
                ECSL2(i)=rsl*2^(-
xsl(i)/1000/xslh)*(paq+t/365*(R2(i)/np));
                ECSD(i)=rsd*2^(-dp(i)/dph)*(paq*np+t/365*(R(i)));
                ECSD2(i)=rsd*2^(-dp(i)/dph)*(paq*np+t/365*(R2(i)));

                ECD(i)=rd*2^(-xaq(i)/1000/xaqh)*(R(i));
                ECD2(i)=rd*2^(-xaq(i)/1000/xaqh)*(R2(i));
                EPS(i)=rps*2^(-xps(i)/1000/xpsh)*(.2*R(i));
                EPS2(i)=rps*2^(-xps(i)/1000/xpsh)*(.2*R2(i));

                dh(i)=6+(xt(i)/1000/15)*2; %make this a function of
distance, not in monte carlo

CLabor=((divers*dh(i)*dw*355)+(leaddiverwage*dh(i)*355)+(watchmendai
ly*355)+managersalary+mechsalary+accountsalary); %355 Day work year!
                CStocking=(ppl*d*Vp*np*harv);
                CDivefixed=(pfdg*divers);
                CDivevar=(pvdg*divers*355);
                CTravel=(2*xt(i)/1000*(fec1+fec2)*pfu*355); %Divided
by 1000 because input data was in meters
                CFeed=(Totalfeed(i)*pf)+(Totalfeed2(i)*pf);
                CConcession=Cc;
                CAquapod=(paq*np);
                CInstall=(pi*np);
```

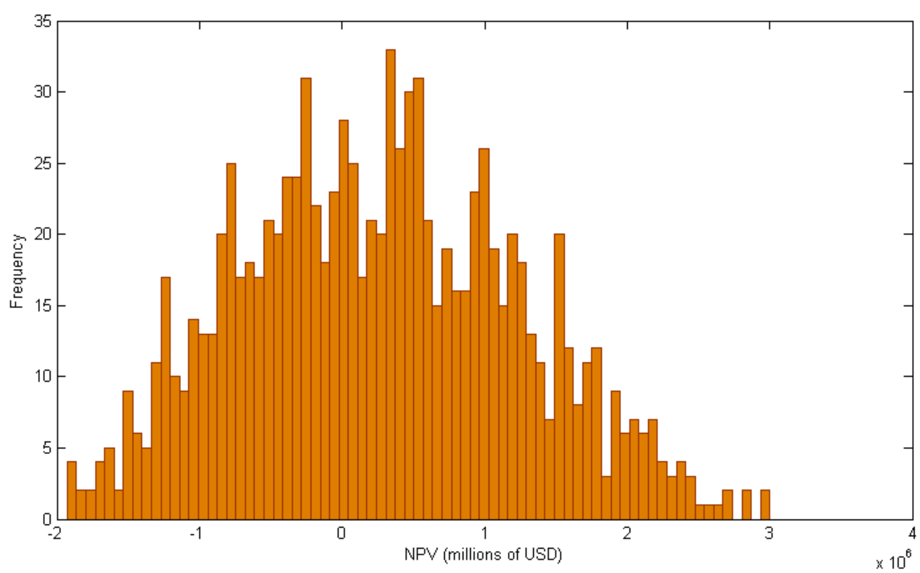
```
C(i,y)=CLabor+CStocking+CAquapod+CDivefixed+CDivevar+CTravel+CFeed+C
Concession+Cpanga+Cplatform+Ctrawler+Crov...

+Cwarehouse+CInstall+ECSL(i)+ECSD(i)+ECD(i)+EPS(i)+ECSL2(i)+ECSD2(i)
+ECD2(i)+EPS2(i); %Costs for one harvest operation (change by
changing to 2*t or *360 - get 5 days off
            end
        end

        %% Final Profits

        prof1=R+R2-C(:,1);
        prof2=R+R2-C(:,2);
        profits=[prof1 prof2*ones(1,19)];

        %% NPV Calculations
        NPVtseries=1:time;%Array for each year of in our business
model
        Discountfactor=NaN(1,length(NPVtseries));
        for i=NPVtseries
            Discountfactor(i)=1/(1+discount).^(i-1);  %Discount
factor each year's profit will be multiplied by
        end
        Discountfactor=repmat(Discountfactor,length(profits),1);
        Discprofits=profits.*Discountfactor;
        NPV=sum(Discprofits,2) ;      %NPV
        NPV_MC(:,it)=NPV; %store monte carlo NPV results in each
patch FINAL RESULTS HERE
        [toc i]
    sorted_MC=sort(NPV_MC,2);
end
E_NPV=mean(NPV_MC,2); %calculates expected NPV at each location,
this is the column we EXPORT TO GIS!!!!!
%
sorted_ENPV=sort(E_NPV,1);
```

## F. ENPV Histograms for Alternative Management Scenarios

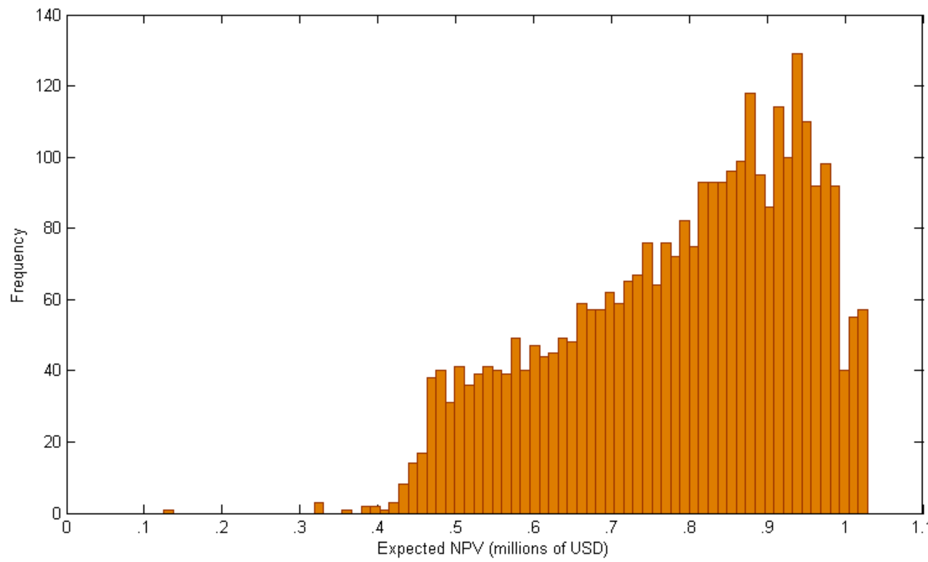
Appendix F1. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario B when feed costs are reduced by 50 percent in our artisanal model.



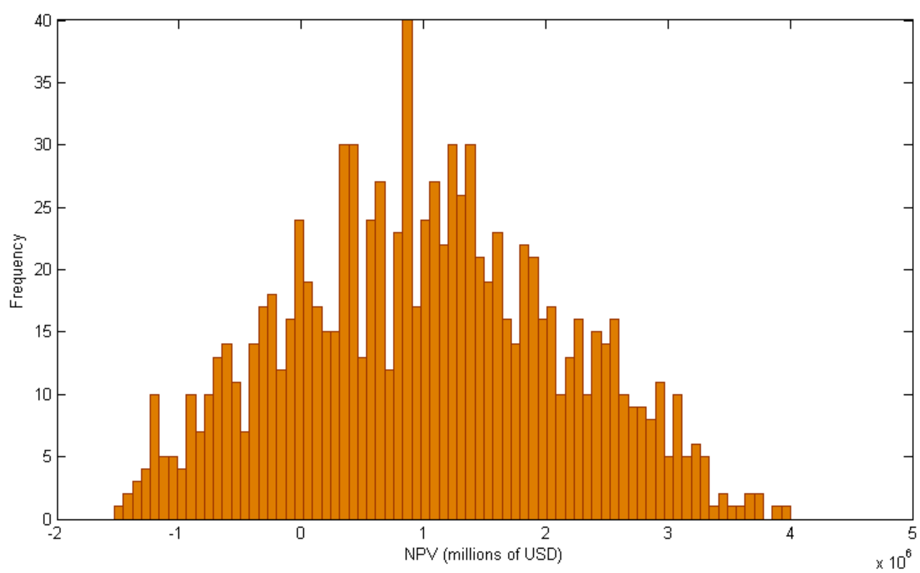

Appendix F2. Histogram depicting the distribution of simulated NPVs for one site (#250) within the Bay of La Paz for scenario B when feed costs are reduced by 50 percent in our artisanal model.



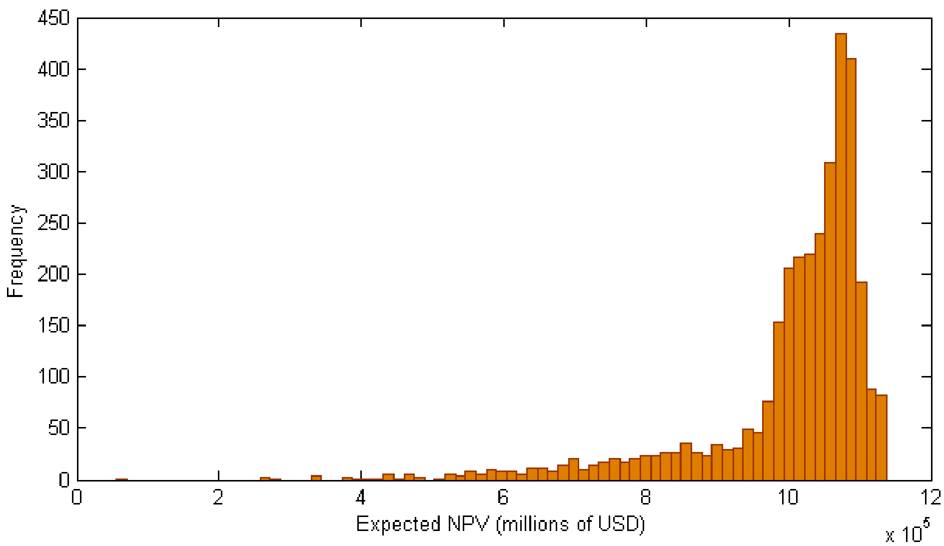
Appendix F3. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario C when feed costs are eliminated in our artisanal model.



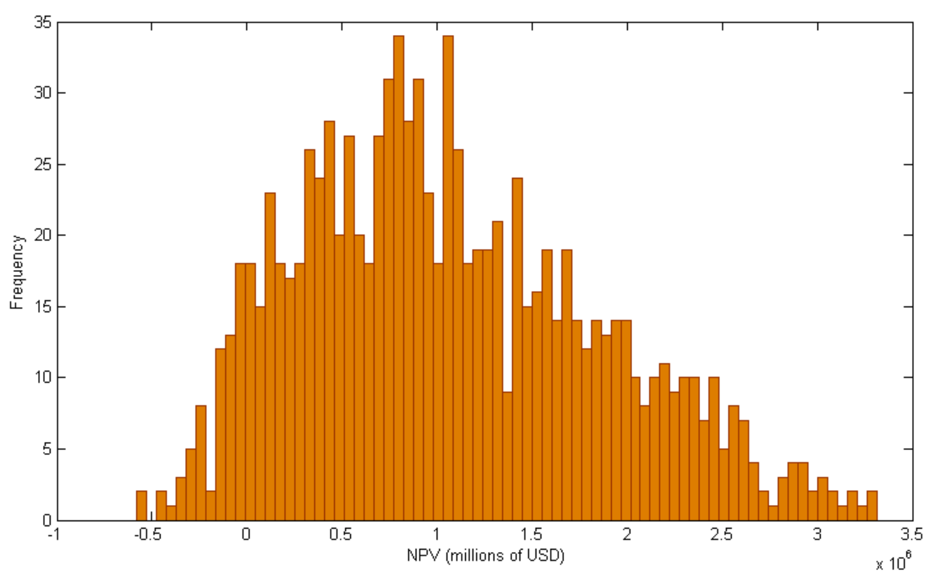

Appendix F4. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario C when feed costs are eliminated in our artisanal model.



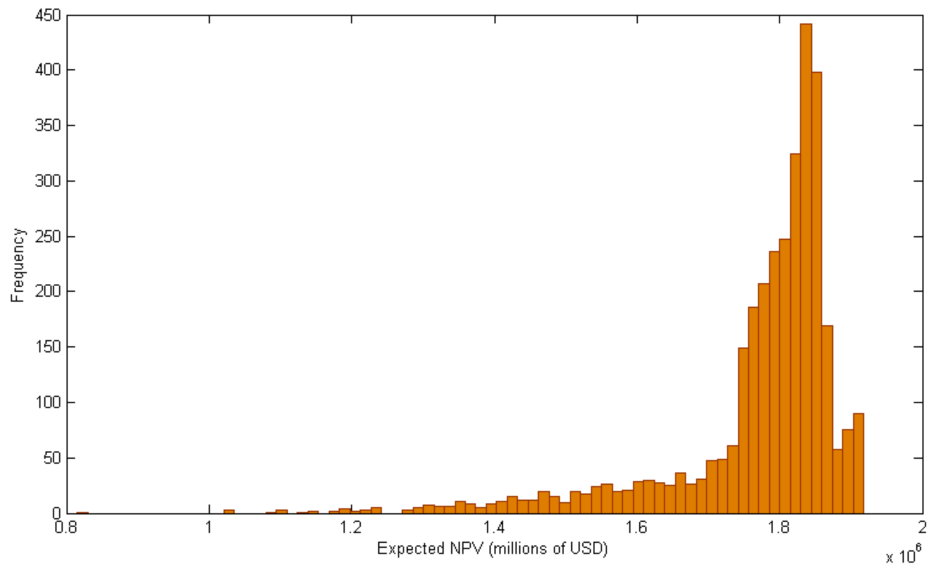
Appendix F5. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario D when dive labor is reduced by one-third in our artisanal model.



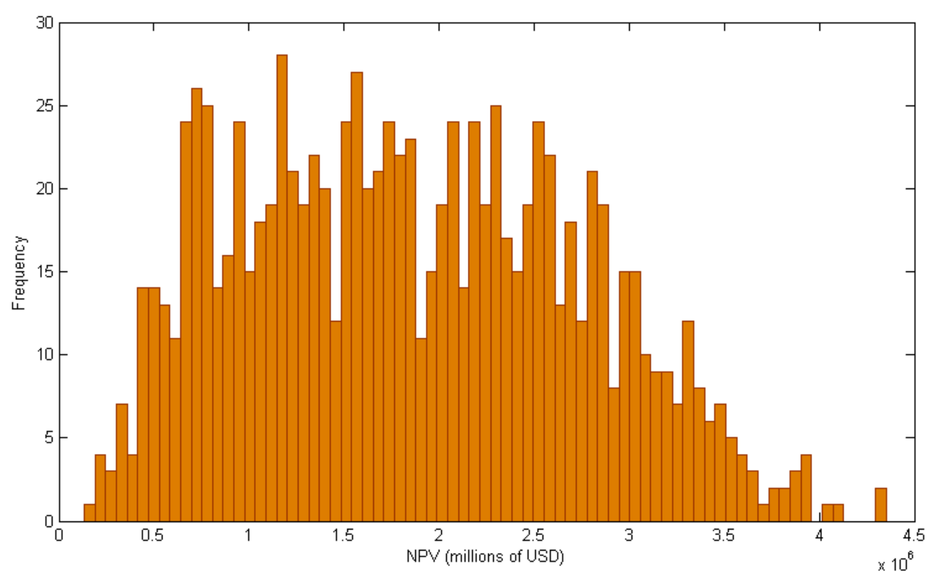

Appendix F6. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario D when dive labor is reduced by one-third in our artisanal model.



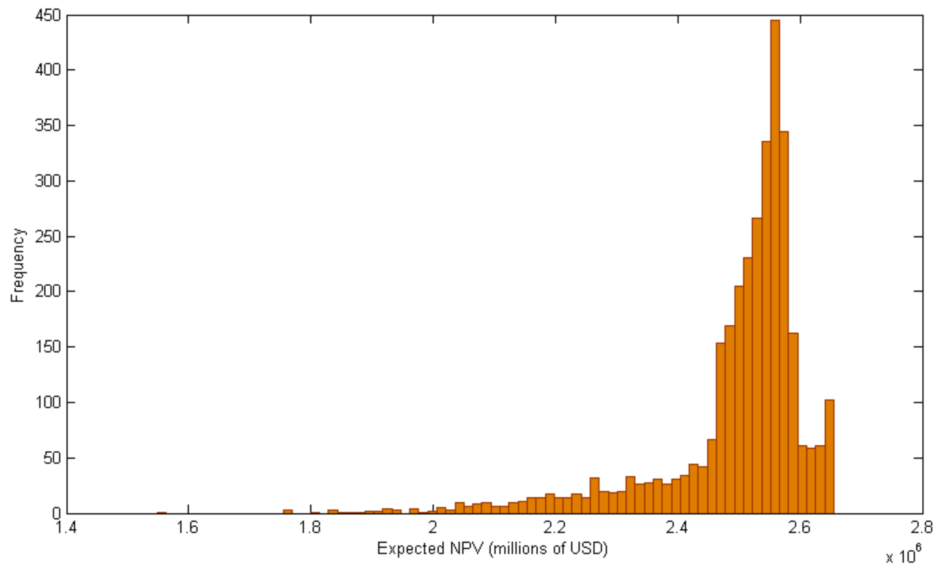
Appendix F7. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario E when feed costs are reduced by 50 percent and dive labor is reduced by one-third n our artisanal model.



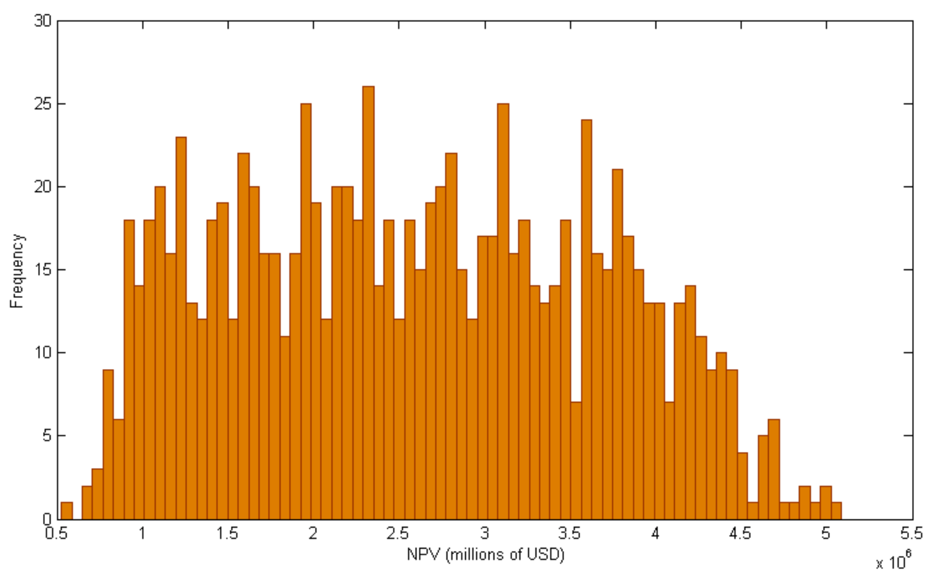

Appendix F8. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario E when feed costs are reduced by 50 percent and dive labor is reduced by one-third n our artisanal model.



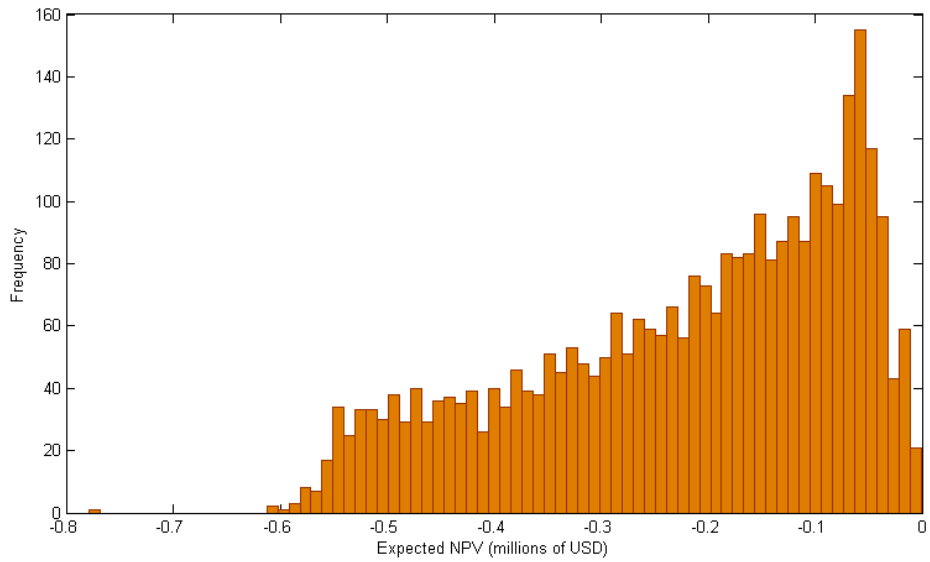
Appendix F9. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario F when feed cost are eliminated and dive labor is reduced by one-third in our artisanal model.



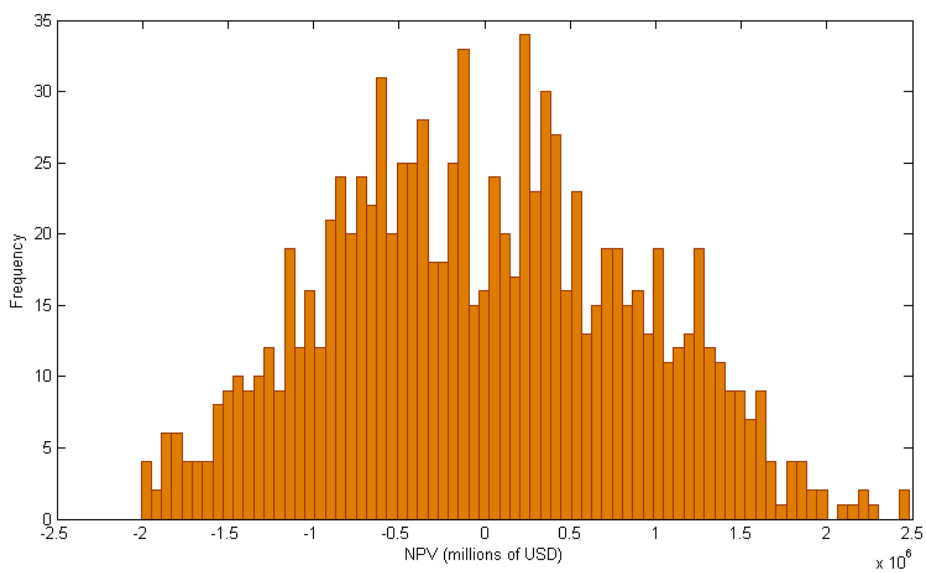

Appendix F10. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario F when feed cost are eliminated and dive labor is reduced by one-third in our artisanal model.



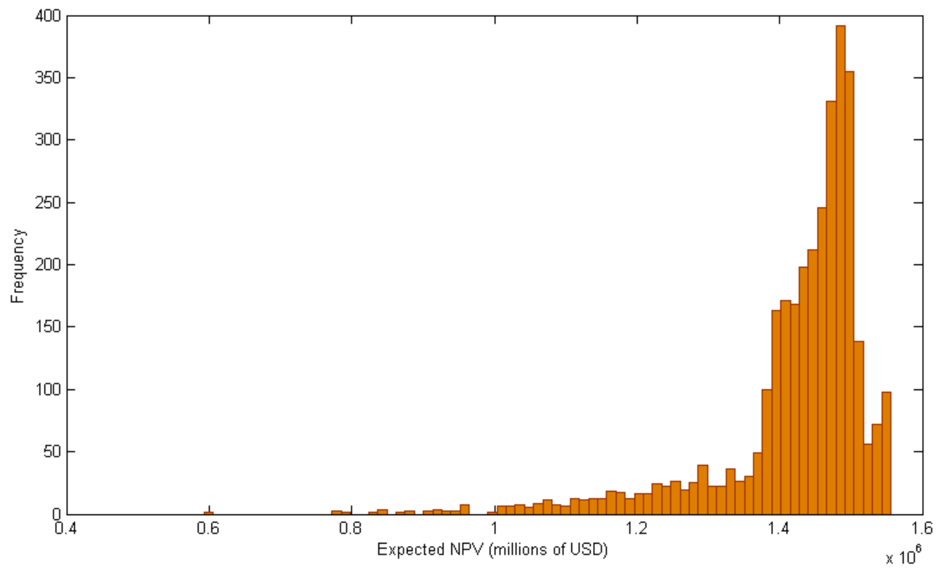
Appendix F11. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario G when feed costs are reduced by 50 percent and shrimp growth rates are reduced by 10 percent in our artisanal model.




Appendix F12. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario G when feed costs are reduced by 50 percent and shrimp growth rates are reduced by 10 percent in our artisanal model.



Appendix F13. Histogram depicting the distribution of ENPVs across all suitable sites within the Bay of La Paz for scenario H when feed costs are reduced by 50percent, dive labor is reduced by one-third, and shrimp growth rates are reduced by 10 percent in our artisanal model.




Appendix F14. Histogram depicting the distribution of simulated NPVs at one site (#250) within the Bay of La Paz for scenario H when feed costs are reduced by 50percent, dive labor is reduced by one-third, and shrimp growth rates are reduced by 10 percent in our artisanal model.