A REGIONAL SCALE SITE SUITABILITY FRAMEWORK FOR AQUACULTURE IN OFFSHORE ZONES

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Dedication page

I want to thank my parents: Milada Oberding-Colton, and Dr Eugene P. Colton, for your unwavering support, prayers, and guidance. Without you I would not be where I am today. Akira Milan, my wonderful son, your smiles and joyful outlook are a beacon to navigate by during stormy times. And my dear friend, and son's mother Keiko, thank you for your unique perspective and continuing cheerleading efforts.

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Abstract

Improper siting of aquaculture developments has led to environmental degradation in many regions where it has been practiced. Though aquaculture has the potential to offset the diminishing quantities of wild-caught fisheries, there are risks inherently associated with this type of production. Some of these risks include pollution of nearby environments by improperly handled wastes, destruction of local-ecosystems from poorly planned facilities, chemical contamination from feed additives, spread of disease, and genetic contamination of wild stock from escaped cultured individuals, among others. Through the use of decision support systems, various frameworks to assist in identifying site suitability have been developed. There have been few published studies that have incorporated environmental, economic, and social concerns when planning for an aquaculture operation. Using publicly available data to ensure cost-effectiveness, a holistic regional-scale site suitability framework for offshore aquaculture using cage technologies has been developed as a first round tool for planners and regional managers. After identification, these locations can be analyzed further to determine precise site selection, thus saving time and costs. A simplified framework allows for multiple stakeholders to participate in, and understand open discussions regarding aquaculture development in their community. It is the purpose of this minimal dataset model, to identify those areas that are compatible with aquaculture at a fundamental level, and thus are appropriate for the more detailed data collection and analysis which would allow further refinement of the selected areas.

Table of Contents

List of Figures

List of Tables

Abbreviations & Definitions

Ahupuaʻa: Traditional Hawaiian land division, similar to a watershed concept, however it included marine waters abutting the watershed boundaries
Big Island: Island of Hawaiʻi
Boolean Overlay Operation: standard decision support tool using Boolean operators (AND, OR)
Cage Culture: Also referred to as "Pen culture," technology used in aquaculture involving completely submerged and enclosed cages to house the production species
DURP: Department of Urban and Regional Planning
EEZ: Exclusive Economic Zone
FAO: United Nations Food and Agriculture Organization
GIS: Geographic Information System
HOARP: Hawaiʻi Offshore Aquaculture Research Project; a joint effort between OI, UH Sea Grant College Program, and numerous state and private institutions
HRS: Hawaiʻi Revised Statues
IRR: Internal Rate of Return
Konohiki: Ruling class in traditional Hawaiian social structure, specific areas of land and ocean were reserved for their sole use
MCDM: Multi-Criteria Decision Making
MCE: Multi-criteria Evaluation
Moi: Hawaiian name of Pacific Threadfin (*Polydactylus sexfilis*)
Nearshore: Aquaculture based closer to shore in depths less that 30m
NOAA: National Oceanic and Atmospheric Administration
OI: Oceanic Institute; non-profit aquaculture research organization located in Waimānalo, Oʻahu
Offshore: When referring to aquaculture, this terms means any area which needs the use of a boat or other craft to access, usually indicated by depths greater than 25m
OWA: Order Weighted Averaging; newly introduced multicriteria decision support tool
Publicly Available Data: Data (particularly GIS data) which is held by government (State and Federal) agencies and institutions. Access to the data should be open to the public with minimal restrictions. Privately held data can be considered 'publically available' if the private party allows access to the data upon request for no fee
Site Selection: The task of identifying the specific location of an aquacultural facility
Site Suitability: The ability of an area to accommodate aquacultural production
SSMP: Site Suitability Modeling Process
UN: United Nations
UNEP: United Nations Environmental Program
WLC: Weighted Linear Combination; standard multicriteria decision support tool
WTP: Willingness to Pay

Chapter 1 Introduction

Improper facility siting has been a critical reason cited for several of the problems associated with aquaculture endeavors worldwide (Avault 1996) as well as in Hawaiʻi (Farber *et al.* 1997). By focusing on proper siting, one can potentially avoid *a priori* many of the traditional problems associated with aquaculture, which include: environmental degradation (Perez *et al.* 2003), incomplete acknowledgement of local cultural issues (Trask 1994), and inappropriate consideration of economics (Farber et al. 1997).

This research shall primarily focus on creating this bridge between the environmental / science-based methodologies for choosing aquaculture sites, and the methods based primarily on social / economic factors. There are numerous framework and models available in the literature, which have been created over the past decade. Most of these have taken years to develop, and are specifically tailored to one zone and or species.

The tool that was used in this analysis is the Multi Criteria Decision Making (MCDM) model. The Food and Agriculture Organization (FAO), a branch of the United Nations (UN), has completed significant work for the use of Geographic Information Systems (GIS) in marine aquaculture (Kapetsky and Aguilar-Manjarrez 2007). Previous efforts utilized a Weighted Linear Combination (WLC) model to determine appropriate offshore site suitability (Young *et al.* 2003, Kapetsky and Aguilar-Manjarrez 2007). It is my belief that the traditional ecologically / biologically focused models can be improved upon by the incorporation of economic and social inputs.

The frame developed for this research is independent of species. That is to say that deciding upon a species *a priori* is less important than deciding upon a culture technology. For sustainable development and management of offshore aquaculture facilities, it is prudent to utilize a native species. The reason for the choice of the animal is multifold:

- The native species will have an established history in the area, it will be well accepted and sought after by the local market and may have potential for export (Kam *et al.* 2003);
- The use of a native species limits the regulatory and environmental difficulties with introducing a non-native species for culture in the local area;
- The use of native species opens the economic potential for fisheries stock enhancement as well as the more traditional end-consumer (restaurants, wholesale) market (Ziemann 2004).

The purpose of this research was to establish a cost-effective, easy-to-understand, and transferable 'first-pass' framework for site suitability of aquaculture facilities in offshore areas, using the island of Oʻahu, Hawaiʻi as the test area. A 'first-pass' framework is meant to identify all potential areas around a broad geographic area (island-wide), based on the simplest set of inputs. Once all potential areas are identified using this low-cost framework, then interested parties can focus limited resources on more detailed, and costly, in depth studies of particular zones which have already 'passed' scrutiny for basic aquaculture requirements (limited resource use-conflicts, compatible with rearing technology, and economically feasible).

The establishment of a standardized protocol for aquaculture site suitability will facilitate the sustainable spread of the industry. A simple framework will also be less intimidating for non-scientists, and would thus be more likely to be adopted and accepted by multiple stakeholders in this field (i.e. interested Hawaiian cultural rights groups).

The scope of this project was limited. It was not the intention of this project to resolve long standing native Hawaiian land claim issues involving the use of Ceded Lands. This project utilized the definitions and assumptions outlined in the Hawaii Revised Statutes (HRS) referring to land use restrictions and definitions (HRS § 0004). Neither did this framework identify specific sites for farm location (i.e. a site selection framework on a local scale), since the marine data available coupled with the minimal dataset nature of the project preclude it from identifying specific sites. However, it does identify suitable areas for further investigation on a regional scale (island/State-wide).

This framework was aimed primarily at an academic audience. It is believed that two additional audiences would be interested in the work:

1. Workers at state level agencies who are involved in the planning and permitting process of aquaculture. By understanding and having at their disposal a simple-easy-to-use general tool, they will be better able to make sustainable decisions regarding aquaculture.
2. Regional planners and aquaculturists working in the private sector. By providing a simple easily transportable tool, the choices of where to develop aquaculture facilities will be made easier to defend and more streamlined, particularly when interfacing with

civil servants, and potential opposition groups, such as environmentalists and cultural advocates.

Chapter 2 Historical Aquaculture

Due to increased pressures, wild fish stocks have been declining in recent years. Numerous fisheries worldwide are nearing collapse and several have had their catch limits severely reduced or even been closed (Subasinghe 2006, Kjærsgaard 2007, Grau 2004). The demand for fish however, continues to increase. Sustainably practiced aquaculture has the potential to supply this increased demand without an accompanying environmental degradation (Grau 2004, Séligny *et al.* 2006).

History and the Blue Revolution

Aquaculture, since it's modern resurgence dubbed the "Blue Revolution," has been touted as a panacea to the world's growing desire for protein (Subasinghe 2006). The ancient Hawaiians supplemented their fishing by integrating fishponds into their local ecological management processes. There is low likelihood that any large-scale fishponds such as those observed during the Hawaiian kingdom Era will ever be built again because of the high cost of land, the complex permitting process, and the low return on investment associated with extensive aquaculture in fishponds (Leung *et al.* 2002). However, aquaculture remains an important facet in Hawaii's future. Per capita, Hawai'i residents consume three times the national average of fish per year. With over 75% of all the fish consumed in Hawai'i being imported (Billig 2007), a vast deficit indicates the potential market for the domestic propagation of fish in Hawai'i. The Hawaiian Islands have limited land resources, and are faced with increased urbanization; aquaculture can have a significant role in the state's sustainable agriculture program.

Traditionally, most aquaculture around the world was used to supplement wild fisheries catches. During recent years more reports have been produced which indicate that wild-fisheries are in decline or entire collapse (Wijkström *et al.* 2004, Séligny et al. 2006). With wild fisheries in collapse due to pressure from overfishing, pollution, and environmental change, sustainable aquaculture has the potential to become an increasing source of fish and other aquatic sourced products (Séligny et al. 2006).

Hawaiian fisheries have not been spared the decline observed in other parts of the world (Wilkinson 2004, Worm *et al.* 2006). As catches decline, the price of fish both locally caught and imported, will continue to increase. With political instability around the world affecting global commerce (evidenced in the energy sector), the reliance on imported fish could be alleviated by growth in local aquaculture. The private sector is beginning to focus on the concept of sustainability in development. Nationally, Wal-Mart the largest retailer in the United States recently began a program in cooperation with the Marine Stewardship Council, whereby all of its seafood (including aquacultured products) will be sourced, labeled and independently confirmed as originating in sustainably managed fisheries (Wal-Mart and Marine Stewardship Council 2006).

Aquaculture appears to have entered the records simultaneously in both Europe and Asia about 2000 B.C. The Chinese are credited with the first fish culture, that of the common carp (*Cyprinus caprio*; (Hora and Pillay 1962)). During the 6th century, the name of a Tang emperor was the same as the name for the common carp; hence, other species had to be investigated for rearing. In addition, due to the difficult nature of distinguishing young fry of differing carp species, the Chinese developed polyculture (Avault 1996).

As Chinese culture spread throughout Asia, the techniques for culturing of aquatic species spread with it. Milkfish (*Chanos chanos*) became the most widespread of all brackish water fish in Southeast Asia (Taiwan, the Philippines, and Indonesia; (Hora and Pillay 1962)). In India of the 3rd century B.C.E., 75 different species of fish and shrimps were described as being culturable in water temperatures of 15C year-round. In Cambodia, bamboo enclosures placed in running water were the forerunners of modern cage culture. Japan has some of the most diverse aquaculture history outside of China. The Japanese have a history of experimenting with the culture of nearly every edible species of aquatic organism. The Japanese also had a pivotal role in the development of the ornamental industry with the culture of *Koi* carp. In 1934, the Japanese began modern shrimp culture by successfully spawning and rearing of the *kuruma* shrimp (*Paneous japonicus*; (Kafuku and Ikenoue 1983).

Aquaculture also developed concurrently in Europe around 2000B.C.E. The Romans developed shellfish culture by seeding ponds with young oysters caught on the shores of the Adriatic Sea (Avault 1996). The progress of aquaculture halted with the fall of the Roman Empire and the ensuing Dark Ages. The widespread development of fish culture began again during the Middle Ages in continental Europe. The common carp was cultured in monasteries and spread primarily in central Europe (modern day Czech Republic, Slovakia, Austria, Germany, Romania, Hungary, and Poland). Bohemia and Moravia (then part of the Austrian

Empire) were famous for their carp farming during the 16th century, and had over 180,000 ha of fish-ponds

Other species including various types of eel and salmon were successfully cultured in the last century. The Europeans have also imported two species of American crawfish (*Pacifistacu leniusculus* and *Procambarus clarkii*) to replace the native variety *Astacus astacus*, whose populations were decimated in the early 1970s by a fungal disease (Avault 1996).

Aquaculture is believed to be a relatively new endeavor in both South America and Africa (Avault 1996). African tilapia ponds receive very little management and are often overcrowded with young tilapia. South American aquaculture has been primarily extensive until the 1980s, when various countries began concerted efforts to develop the industry. In the early 1990s, Chile produced 34,000 mt of net-pen cultured Atlantic salmon, making it the primary world supplier of such salmon. The culture of shrimp had also been rapidly expanding in various countries of Central and South America until the early to mid 1990s. During this time, the rapid spread of disease (white spot syndrome and Taura virus) devastated the shrimp culture industry (Kautsky *et al.* 2000, Fast and Menasveta 2000).

In North America, aquaculture is also a new endeavor dating back 150 years (Parker 1989). In the 1850s, immigrants from around the Adriatic Sea began transplanting young oysters to previously depleted oyster beds. The culture of trout began with the artificial fertilization and hatching of brook trout. These early efforts were concerned primarily with the restocking of natural waters, which had become depleted from overharvesting (Parker 1989). In the 1950s, catfish farming began in earnest in the southern U.S. with about 200 ha devoted to ponds; by the 1990s, 62,800 ha of ponds were in production. These ponds produce nearly the entire commercial supply of catfish for the U.S. market (Avault 1996).

Asia is the world leader in the culture of aquatic organisms. In 1985, Asia was responsible for producing 6,139,300 mt of aquaculture products, the world total including Asia during 1985 was 7,915,700 mt (Nash 1988). The advent and introduction of intensive shrimp culture has altered the economic and environmental dynamics of the region (Paw and Chua 1991). Shrimp is the most valuable aquacultured animal, and hence has increased its contribution to the global supply from 5% to over 30% between 1982 and 1994 (Anderson and Fong 1997).

Hawaiian Aquaculture

Hawai'i has a long history of aquaculture. Of all the Polynesian cultures, Hawai'i had the most developed forms of aquaculture. This rich history and cultural acceptance of farmed species should allow for the continued development of aquaculture within the state. A review of historical culture practices provides the basis for understanding why offshore aquaculture is a natural evolution from the coastal-based technologies present in earlier times.

Historical

The evolution of Hawaiian fishponds stems from natural and man-made fish traps, which were prevalent in Oceania (Farber et al. 1997). The Hawaiians utilized aquaculture as a supplement to their wild-caught fish, and as a ready supply of valuable species for the ruling classes (Apple *et al.* 1975). More than any other culture found in Oceania, the Hawaiians developed an extensively integrated, advanced form of aquaculture (Farber et al. 1997). By the time of first Western contact, *ahupua'a* land divisions on most of the islands had fishponds associated with them. An ahupuaa's wealth and prosperity was determined by the quantity and productivity of the fishponds which were located within its boundaries (Kelly *et al.* 2000).

There is no definitive historical record as to the origins of Hawaiian fishponds. The earliest mention of fishponds in the Hawaiian islands comes from O'ahu in the 13th century (Kikiuichi 1973). The construction of the first fishponds are attributed to the gods *Kāne* and *Kanaloa*, who came from *Kahiki* (originally a term for Tahiti). Only 23 fishponds were recognized as being built by man or at the direction of a ruler. The rest of the fishponds are credited either to gods, or the *Menehune*, who were the first inhabitants of Hawai'i. The *Menehune* were also believed to have constructed many of the older civil engineering projects, always utilizing stones for their work, and completing their tasks within the span of one night (Farber et al. 1997). These legends attest to the ancient nature of fishpond culture in Hawaii since the actual origin of many fishponds are shrouded in myth.

There were six different forms of fishponds developed by the Hawaiians. Though the brackish/salt-water ponds are probably the best known, the Hawaiians, developed fresh-water fishponds as well (Farber et al. 1997). These were integrated with the Hawaiian wetland agricultural practices, which centered on the growth of taro. The Hawaiians favored brackish-water fish as it was believed they possessed more flavorful flesh (Farber et al. 1997). Though direct comparisons of current water quality conditions cannot be made with the conditions which existed during the Ancient Hawaiian Kingdom, the brackish-water fishponds were believed to be the most productive (Apple et al. 1975). These constructed ecosystems surpassed the productivity of natural estuaries by 100 fold for optimal growth parameters of juvenile fish as well as algae (Apple et al. 1975). Three fishpond-types were freshwater, brackish water, and saltwater. This variety of pond-types allowed the Hawaiians to efficiently utilize the limited space and resources available to them and indicate the understanding and ingenuity of the Hawaiians for utilizing their limited resources to the full potential (Apple et al. 1975, Kelly et al. 2000).

A variety of species were cultivated by the Hawaiians in their ponds. These included numerous fish species such as milkfish, mullet, shrimp and eel among others, as well as diverse species of edible freshwater and seawater algae. The most prominent species that were cultured in ancient times were *moi* (*Polydactylus sexfilis*) and mullet (*Mugil cephalus*) (Figures 1 and 2 respectively). These were favored for consumption and were thus produced in the largest quantities (Tamaru *et al.* 1997).

The freshwater ponds were called *loko wai*, *loko i'a kalo*.

- *Loko wai* were simply inland lakes and swamps, with some modified ditches, which connected them to another source of water such as ocean, a stream, or a river (Farber et al. 1997). These were exclusively royal ponds, with all fish caught in them intended for use by the ruling classes (Apple et al. 1975). The average size was half an acre (Farber et al. 1997) and were used to raise *'o'opu (Stenogobius hawaiiensis, Awaous guamensis, Lentipes concolor, and Sicyopterus stimpsoni)* (Keala *et al.* 2007).

Figure 1 ***Moi*** **(*****Polydactylus sexfilis*****), (NOAA 2007)**

Figure 2 Mullet (***Mugil cephalus*****), (Tamaru et al. 1997)**

- *Loko i'a kalo* were true polyculture ponds. These were taro patches that were also utilized concurrently for fish production. These were non-royal ponds, but local chiefs could establish sole use of them (Apple et al. 1975). These were used to raise *'o'opu, 'ama'ama (Mugil cephalus), and āholehole* (*Kuhlia sandvicensis*) (Keala et al. 2007).

The brackish water ponds were referred to as *loko pu'uone*, and *kaheka and hapunapuna*.

- *Loko pu'uone* were ponds, which were constructed by creating sand ridges, which are parallel to the coast. Ditches or streams then connected these ponds to the ocean. Apple and Kikuichi (1975) classified these ponds as being exclusively for the production of royal fish. The sizes ranged from 'small' (which required little construction) to large 300 acre sites (Farber et al. 1997). The fish raised here were: *'ama'ama, "awa (Bodianus bilunulatus), āholehole, papio or ulua (Aprions virescens*), *'o'io (Albula vulpes*) *, nehu (Stolephorus purpureus*), *'awa 'aua (Elops hawaiensis), 'o'opu, kaku (Sphyraena barracuda*)*, moi, and weke* (*Mulloidichthys* spp) (Keala et al. 2007).
- *Kaheka and hapunapuna* were ponds, which had been isolated natural pools with subterranean connections to the ocean. Though some sources classify them as freshwater ponds, Maciolek and Bonk (1973) developed the term achialine, meaning "near the sea" to classify ponds which have brackish water, tidal rhythms, and no "surface connection to the sea." The *kaheka and hapunapuna* were utilized for bathing and sometimes as sources of potable water, while others were developed for aquaculture, as most contain populations of shellfish and bivalves (Maciolek and Bonk 1974).

The saltwater ponds were known as *loko ʻume'iki* and *loko kuapa*.

- *Loko ʻume'iki* were the ponds that are traditionally associated with ponds found elsewhere in Oceania (Apple et al. 1975), and are considered more of a fish trap than a true fishpond (Keala et al. 2007). These ponds are made of walls of coral or stone with multiple lanes leading to and from the ocean, which were submerged during high tide. These ponds relied on tidal currents to flush water and fish in and out of the structure, where they would be harvested in the lanes with nets as the tides ebbed and flowed. These fishponds, and the fish produced within it, were at times accessible for consumption by the common families. The average size of the inward lane was 45.5 ft long, 21.5 ft wide and 5.5 ft opening, while the outward lane was 21ft long, 10.5 ft wide, and 4ft at the opening (Farber et al. 1997). As they were fish traps, most fish associated with reef flats could be reared including: *kala (Naso* spp)*, palani (Acanthurus dussumieri) and manini (Acanthurus triostegus) (Keala et al. 2007).*
- *Loko kuapa* were ponds, which had a wall facing the ocean that formed an arc and was connected to the shore at its two endpoints. These ponds were exclusively for royal use and were considered to be an advancement over the *loko ʻume'iki*, as the flow of fish with the tideswere controlled by a gate called the *makaha*. The size of the ponds varied from 1 to more than 523 acres (Farber et al. 1997). Numerous fish associated with reef flats includes: *kala, palani and manini*. Though not associated with reef flats other fish included: *kahala (Seriola rivoliana), kumu (Parupeneus porphyreus), moano (Parupeneus multifasciatus), weke ula (Mulliodes pflugeri*)*, uhu (Chlorurus sordidus), hinalea*

(Thalassoma spp*),* surgeonfish, crevally, goatfish*, and puhi (Gymnothorax melatremus)* (Keala et al. 2007).

The walls were often designed to be able to withstand high tide and were wider at their base than at the surface (Apple et al. 1975). The most massive wall was found in Kona, and measured 11 meters at its base. The average pond walls contained over 955 cubic meters of stacked stone and coral (Kikiuichi 1973). Some walls were constructed within the confines of the pond itself. These walls were often less massive and were designed for the segregation of the fish (Apple et al. 1975). The original *makaha* was simply a non-movable opening in the wall with vertically aligned stakes which allowed water and fry up to half an inch long to pass. A typical pond had one or two *makaha*, which were placed, based on prevailing ocean currents; cases of ponds with up to seven *makaha* have been documented. Apple and Kikuichi (1975) hypothesized that the *makaha* evolved out of the grates used for water control in upland taro ponds. In order to prevent theft, guardhouses, called *hale ka'i*, were integrated into the construction of the ponds. These were utilized by the pond keepers, who were charged with maintaining the ponds and their cultured species populations (stocking and harvesting). In post European contact, the *makaha* developed into a movable gate with double sets of grates (similar in concept to an airlock) that allowed for the capture of fish in the space between the two grates (Apple et al. 1975), (Farber et al. 1997). The walls were constructed to allow some water circulation between the ocean and the pond; additionally, two openings located at the ends of the walls were utilized for the flushing of sediments (Summers 1964).

The Hawaiians practiced extensive and in some cases semi-intensive aquaculture, as they relied not only on the growth of algae (fertilized with nutrients from their agricultural plots upstream) as feed for their chosen aquaculture species (Apple et al. 1975), but also actively supplied the fish with feed such as sweet potato (Kelly et al. 2000). As the fry and young of various species are often difficult to distinguish, Hawaiian aquaculture was consistently polyculture, in that different fish species were cultured together in the same pond.

DHM Inc (1990) produced a historical survey of all the Hawaiian island's fishponds and identified 488 total ponds on the six main Hawaiian Islands. O'ahu and Hawai'i had the most with 178 and 138 ponds respectively (DHM Planners Inc. and Bernice Pauahi Bishop Museum 1989).

Apple and Kikuichi (1975), using historical records estimated that in 1800, there were 350 ponds in operation, with an average pond size of 15 acres, and 350 pounds of fish produced per acre per year yielding a total of 1,758,750 pounds of fish. The first studies of fishponds were produced by Cobb in 1900 as part of the United States Fisheries Commission (Cobb 1902). His initial report stated that of 158 fishponds surveyed, 99 were in use. This total number did not include the Islands of Kauai or Maui however; hence, the productivity estimates produced have been disputed since their publication. Cobb estimated that the 99 active fishponds in use produced 682,464 pounds. When he resurveyed the islands in 1903 he indicated that only 86 ponds were operating and producing 72,953 pounds (Cobb 1903). Several studies produced in 1977, 1992, and 1997 have reexamined the Cobb data and each has estimated a different value for average fish production. The values of average production range from 176 to 209 pounds per acre per year (Farber et al. 1997, Madden and Paulson 1972, Wyban and Wyban 1989).

Overall, the current status of the Hawaiian fishponds is poor. The 1990 study by DHM indicated that of the 488 total ancient Hawaiian fishponds identified, six were still in production yielding a total of 31,639 pounds of fish annually. Their study divided the physical condition of the fishponds into a number of categories ranging from sites that were intact and excellent condition (Class I) to those where no visible remains exist (Class III). Twenty-five ponds, 18 of which are on Hawai'i, were registered as Class I. In contrast, O'ahu had 134 of the 200 Class III type fishponds. The primary reasons cited for the status of fishponds were environmental changes such as, tsunamis, soil erosion from agriculture (including deforestation), invasive species encroachment (primarily mangroves), and land reclamation due to urban development (DHM Planners Inc. and Bernice Pauahi Bishop Museum 1989, Farber et al. 1997). Figure 3 indicates the change in fishponds and the ecosystem in general in Kaneohe Bay between 1928 and 1971. Figure 4 is a map, which further elucidates the loss of fishponds over the same period of time.

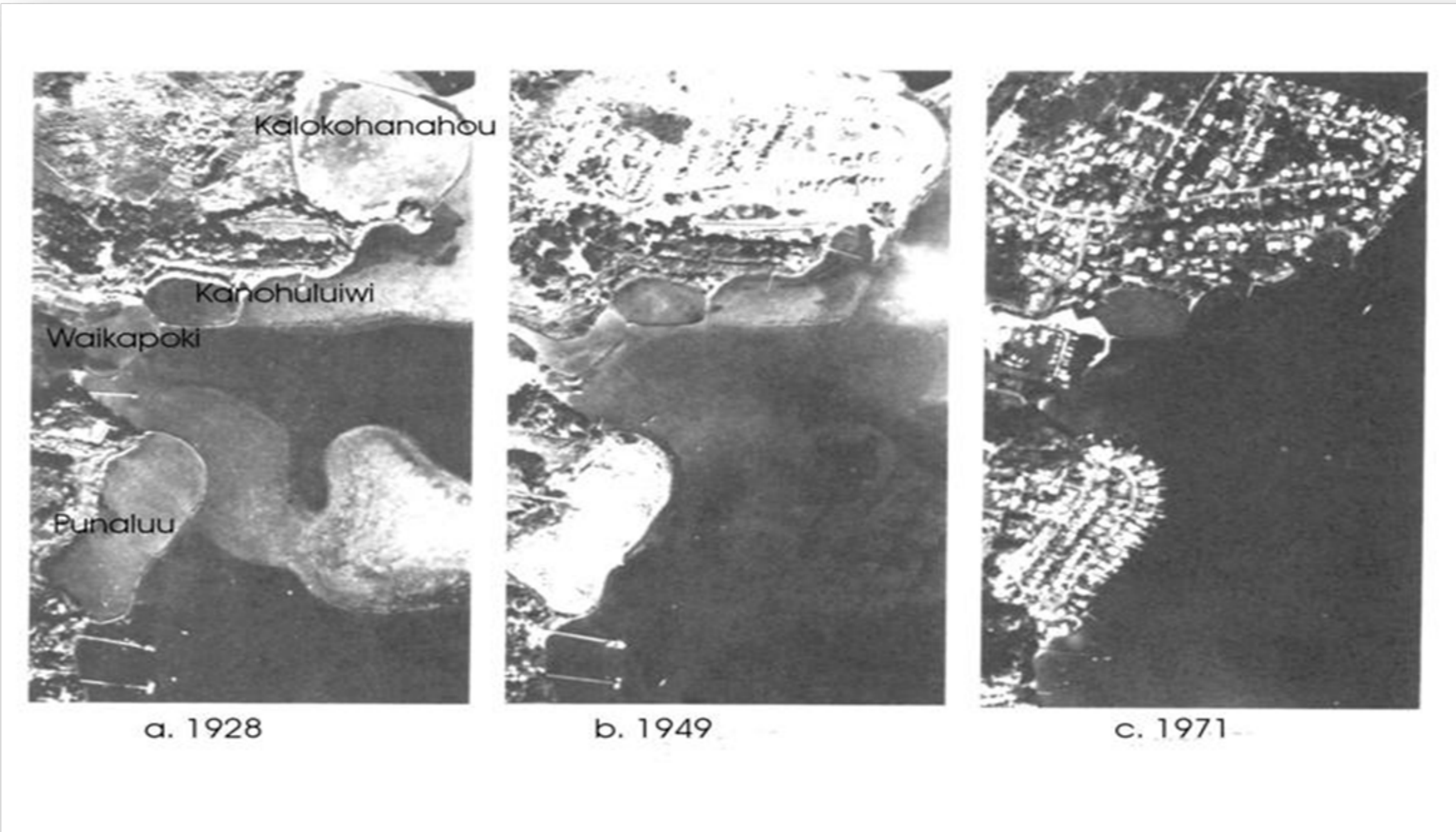

Figure 3 Kāneʻohe Bay Fishponds, 1928-1971, (Tamaru 2006)

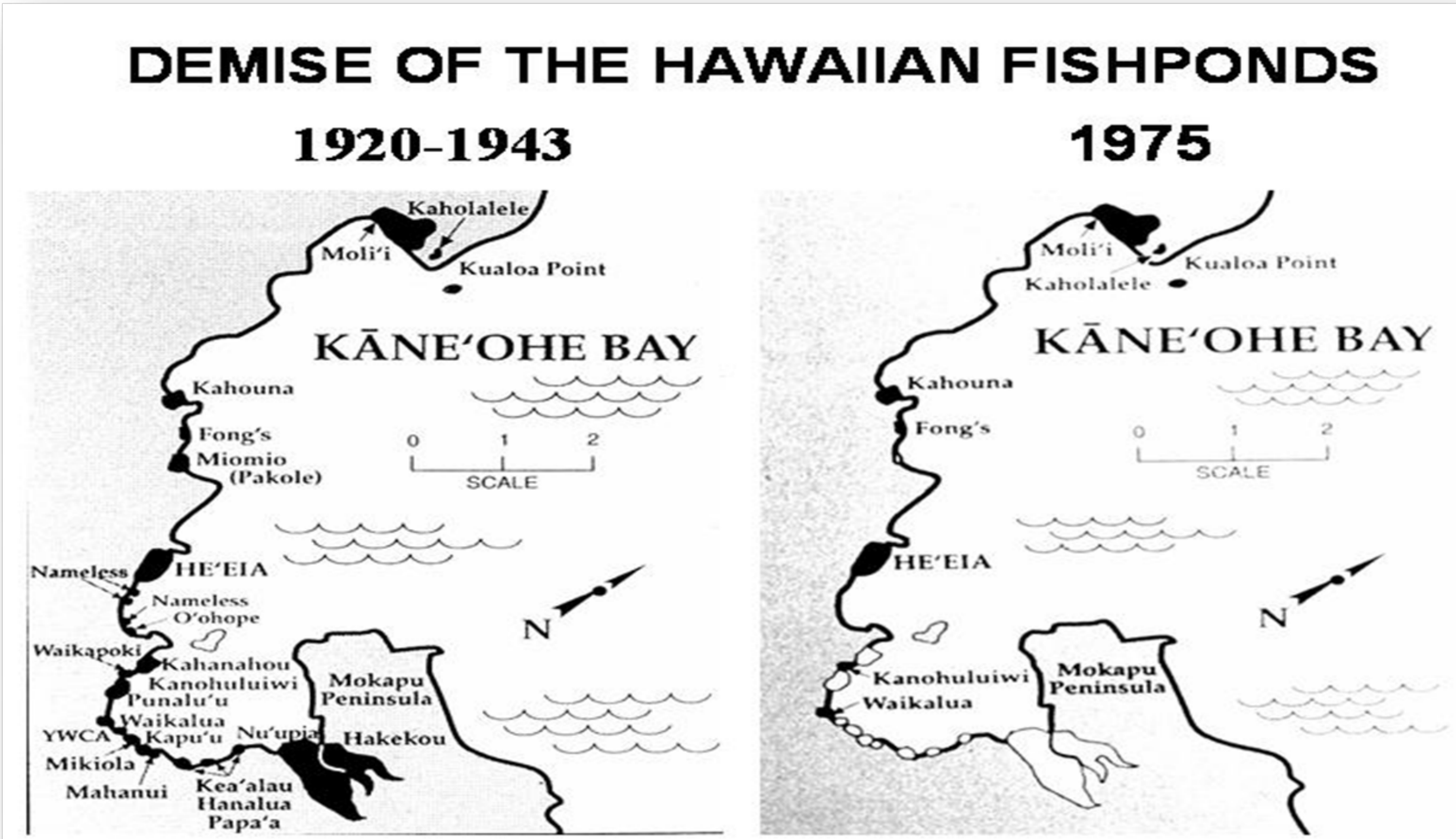

Figure 4 Map of Kāne'ohe Fishponds 1920-1975, (Tamaru 2006)

Modern

Modern aquaculture in Hawai'i began in 1960, with the Oceanic Institutes studies of mullet (Wyban and Wyban 1989). In the 1970s the State of Hawai'i began research into culture techniques of freshwater prawn (*Macrobrachium resonbergii*). In the mid 1970s, the techniques had evolved to the point that technological transfer was initiated to the public. By 1976, 14 freshwater prawn farms were in operation producing 1,000-1,500 kg/ha/year from 0.4 acre earthen ponds. Though few of these original 14 farms existed in 1989, with improved technology and stocking densities, a small farm could expect to produce 4,500 kg/ha/year of freshwater prawn (Wyban and Wyban 1989).

By the mid 1980s, there were 36 producing farms on O'ahu, and several high tech startups on Hawai'i, which included abalone and Spirulina (Wyban and Wyban 1989). In 1988 there were 423 people employed in aquaculture with the industry generating $18.8 million in revenue. Some of the limitations that the industry had begun to encounter at this time were high production costs, lack of investment capital, disease and feed costs (Wyban and Wyban 1989).

During the 1990s, work continued on improving shrimp production, with emphasis on SPF (Specific Pathogen Free) broodstock, higher stocking densities, and different species (*Litopenaeus vannamei*). In addition to pushing the modern technological aspects of aquaculture, the 1990s saw a resurgence in Hawaiian culture, which included renewed interest in traditional fishpond revitalization (Farber et al. 1997, HI ADP 2009). However, most of these efforts were unsuccessful (Farber et al. 1997), mainly due to various complications inherent in the modern political and governmental systems (complex permitting process and small economic profit margins).

By 2003, the size of Hawaii's aquaculture industry had grown to $27.7 million. There were over 100 farms actively producing a variety of species for both commercial and research production employing over 942 people. There are numerous species being cultured and produced in Hawai'i today (Table 1), with some of the farmed products including marine and freshwater shrimp species, m*oi,* as well as algae and other non-food products such as pearl oysters and aquarium species (HI ADP 2009).

Due to the current social and economic climate in Hawai'i, the ability to revitalize and develop the ancient fishponds for modern aquaculture is limited. The location of aquacultural production has been determined by a combination of requirements since the earliest aquatic species were cultured. Some of these requirements have included:

- Economic
- Environmental restrictions
- Social

Though the broad categorization of criteria remain the same, the conditions in modern Hawai'i offer a different set of constraints on the placement of aquaculture production sites.

Table 1. Aquaculture Produced Species in Hawai'i (Hawaii Aquaculture Development Program 2009)

Finfish	Shellfish	Bivalves	Algae	Other
Milkfish (*Chanos chanos*)	Marine shrimp for food (*Penaeus vannamei)*	Seed clams (*Mercenaria mercenaria*)	Marine ornamental fish and plants (various species)	Seahorses (various species)
moi (Pacific threadfin, *Polydactis sexflis*)	Broodstock and juvenile shrimp (L. vannamei, L. monodon, L. stylirostris)	Abalone (red, *Haliotus rufens* and Japanese, *Haliotus discus hanai*)	Seaweed or sea vegetables (*Gracilaria* sp.)	Seed pearl oysters (*Pinctada fucata, P. margartifera*
Carp (*Ctenopharyngodon idellus*, *Hypothalmichthys mollitrix*)	Freshwater prawns (*Macrobrachium rosenbergii*)	Giant clams (*Tridacna* sp.)	Microalgae (*Spirulina* sp., *Hematococcus* sp.)	Tilapia (*Tilapia* sp.)
Catfish (*Clarius fuscus*)	Lobster (*Homarus americanus*)	Seed oysters and clams (*Crassostrea gigas*, *Ostrea edulis*, Mercenaria sp.)		Aquatic snails (*Pomacea* sp.)
Mullet (*Mugil cephalus*)				Freshwater ornamental fish and aquatic plants (various species)
Japanese Flounder (*hirame*, *Parlichthys olivaceus*)				Marine ornamental invertebrates (various species)
Kahala (amberjack, *Seriola rivoliana*)				

Unlike the numerous environmentally integrated styles of fishponds that were in use during the Hawaiian Kingdom era, there are relatively few culture technologies used in Hawaiʻi today. Onshore production is limited to tanks for hatchling and some growout ponds, while offshore there are currently two types of floating and anchored cages, with a third, free-floating cage type being proposed (Gomez 2009). Examples of offshore cage technology in use in Hawaiʻi are the Polar Circle floating system (Kona Blue Water Farms 2003)and the Sea Station 300 (Cates International Inc. 2000), which are shown in Figures 5 and 6. As in the Hawaiian kingdom era, these growout structures represent a significant investment by the operators. Due to advancements in technology, these cages are very robust, and can withstand severe environmental conditions. The Sea Station cages are designed for use in waters over 25m deep, with a capacity to between 600 and 6,000 m^3, currents of 2.25-2.5 knots, Category 4 hurricanes (winds between 210 km/h and 249 km/h), with unlimited fetch (Ocean Spar 2009a). The nearshore cages such as the Polar Circle have slightly more limited environmental parameters, but are nonetheless relatively robust. They can be anchored in 15-30m of water, withstand 2.25-2.5 knot currents, and endure moderate winds and fetch and have a large capacity between 5,000m^3 and 40,000m^3 (Ocean Spar 2009a).

Currently the size of the single offshore *moi* cage operation on Oʻahu is 11.33 ha and produced 544,310 kg of fish in 2007. The owners are seeking to expand to 24.69 ha and thus produce 2,267,961 kg. The Kona Kampachi (Amberjack, *Seriola lalandi*) operation currently has a 36.42ha lease and has been scaling back production from 453,592 kg to 272,155 kg per year due to increased transportation costs (Gomez 2009).

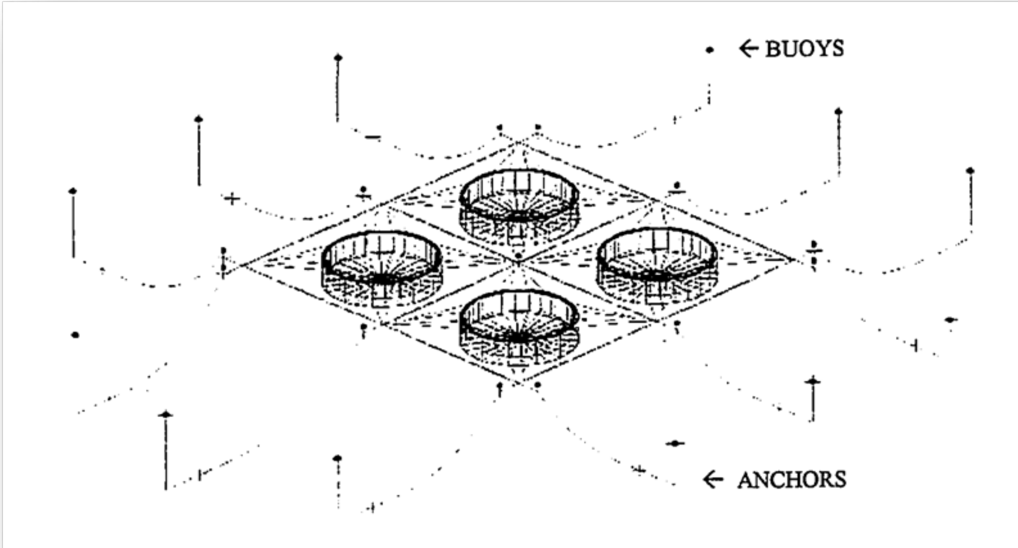

Figure 5 Polar Circle Cage Array, (Kona Blue Water Farms 2003)

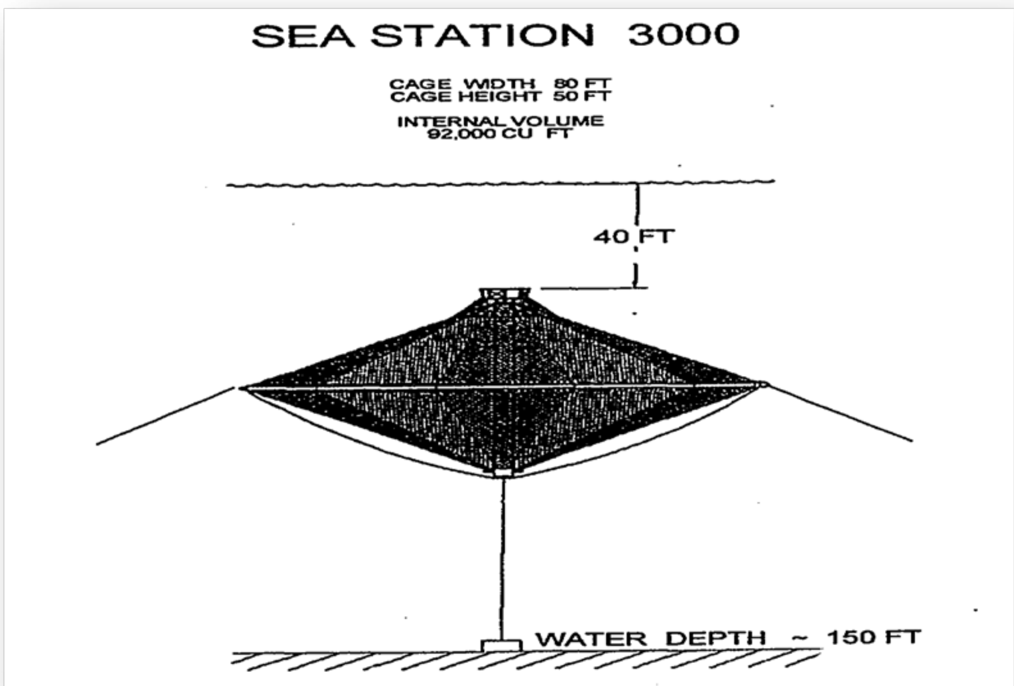

Figure 6 Sea Station 300 Offshore Fish Cage, (Cates International Inc. 2000)

Though the particulars of any one location are dependent on the species of organism and culture in which it is developed, there are some similarities. A standard set of protocols based on the universal environmental management tools and planning theories could potentially be established, which, if basic enough can be translated to any location, and species. This research documents the history of site suitability using Geographic Information Systems (GIS). The focus was on the elucidation of a simplified, transferable, first-pass framework based on the concept of minimal datasets for site suitability of offshore cage culture (Kam et al. 2003, ICRISAT 1983).

Due to numerous factors, including limited space, intensive offshore cage culture is considered the most logical option for the future of aquaculture in Hawaiʻi (Leung 2007). By focusing on a simplified set of protocols, it is believed that the framework can be utilized in multiple locations by multiple parties.

Chapter 3 Impacts of offshore aquaculture

Environmental and Social Effects

The environmental and social impacts that are associated with offshore net-pen aquaculture can be categorized into five broad groups: water column, benthic, chemotherapeutics, genetics and user conflicts. These are the most commonly cited examples of the risks associated with modern aquaculture (Primavera 2006). Proper siting of facilities can alleviate some of these risks.

Water Column

All living organisms produce waste products as a part of their life-cycle. Depending on which environment the organism inhabits determines how its wastes are dealt with. Fish excrete a mixture of both solid and liquid wastes. These wastes contain several components, but of most concern are carbon, nitrogen and phosphorus. Though some wastes accumulate on the benthos, others (ammonia and urea) are dissolved in the water (Primavera 2006).

Water, similar to air, readily disperses compounds. As with other forms of pollution, the farther away from the source, the greater the dilution and dispersal effect. Hence, carbon: nitrogen: phosphorous (C:N:P) ratios measured at the cage surface tend to be high. However, the greater the distance from the cage, the more dilute the nutrients and the smaller the count. As with any medium, there is a limit to the quantity of chemicals that water in oceanic and offshore environments can hold before it becomes supersaturated with the dissolved compound. The local environmental conditions, temperature and current speed (analogous to water exchange rate from traditional onshore aquaculture), determine the water's capacity to absorb the nutrients (Primavera 2006).

The primary problem associated with nutrient loading of the water column is that it acts as a fertilizer for the phytoplankton. An ecosystem (plankton) such as that of the water column can absorb some increase and remain in balance. Certain subspecies of phytoplankton may increase but so will their zooplankton predators and overall the system remains in equilibrium. However, as nutrient levels increase beyond the coping capacity of the ecosystem, the phytoplankton populations tend to grow out of control. These plankton blooms reduce the available oxygen in the water column and create anoxic conditions. If left unchecked, with continuous nutrient additions, the plankton outcompete other species, and eventually even the phytoplankton dies off leaving 'dead zones.' These zones are increasingly found at the mouths of major river systems, with one of the largest being in the Gulf of Mexico at the Mississippi Delta.

The nutrient loading associated with offshore pens in more limited. This is primarily due to two factors, the cages are located in areas which flush well, and the operations themselves are small and located far enough apart from each other that the effects are negligible. If the cages are located in an area that does not have sufficient currents, or in a bay with poor water exchange, there is a real possibility of self pollution. In properly sited and managed farms, the pollution of the water column from nutrient wastes can be limited.

Benthic

Benthic pollution by aquaculture operations can be a more serious concern than water column impacts. Fish feces, though carried by the currents, are heavier than water and settle to the bottom. Additionally, the feed pellets that the fish consume also settle to the bottom. This feed contains high levels of C:N:P in formulation which are optimized for rapid fish growth. This excess feed and feces act as hyper nutrients and fertilize the benthos beneath the cages (Aguado-Gimenez *et al.* 2007).

The benthic surface, such as a hard stony bottoms or a sandy plateau, is an establish ecosystem. The addition of fertilizer (feces and unconsumed feed) can have an impact of the community balance. Several areas can be affected: benthic oxygen consumption, microbial and macrofaunal biomass and community structure, and larger epibenthic organisms. The changes associated with the increased nutrient loads are most often increases in microbial growth (creation of visible microbial mats). Depending on the deposition rate of the nutrients, the system may become overloaded and the nutrients may simply deposit and accumulate on the bottom. The rate of nutrient decomposition depends greatly on the original benthic community as well as the type of feed. As certain feeds make nutrients more available for the fish, these feeds will also break down faster than poorer quality feeds. With increased deposition the sediment geochemistry changes overtime (Aguado-Gimenez et al. 2007).

Depending on environmental conditions, distance from the source of waste tends to dilute the impact. Researchers in 1995 found that significant environmental impacts were limited to within 1km of the cage (Wu 1995). Cates (2000) noted that the HOARP study found significant changes to the benthic community directly beneath the cages when overfeeding took place; however, under normal feeding regimes, the benthic ratios remained the same. There are also annual fluctuations observed in the benthic communities. These occur naturally without the presence of cages. Consequently, the momentary impact observed on the benthic community for a cage cannot be viewed alone; it has to be compared across time.

Chemotherapeutics

Chemotherapeutics cover a broad category of impacts which include feed additives (antibiotics, therapeutants, vitamins), as well as antifouling chemicals applied to the physical cage structures.

The feed additives which are of least concern in this section are the vitamins (B_{12}). The effects of vitamins in the environment are similar to those found in the discussion above about nutrient loading. The main impact of vitamin loading will be to alter the geochemistry of the benthos and water column. Antibiotics however, are a cause for concern. These items are included in the feed as the most efficient way of distributing them to the fish (Molina Dominguez 2001).

The use of antibiotics in animal production has become a popular topic in the mass media and is not limited to aquaculture. As densities of animals increase, the need for antibiotics increases as well. Since most cage culture is intensive, the ability of a pathogen to destroy an entire crop is increased. As the antibiotics are delivered through the feed, some is lost to waste (Shaw *et al.*). This allows the antibiotics to accumulate in the benthos (Molina Dominguez *et al.* 2001). This can substantially alter the microbial communities present and can have lasting impacts even after the operation is moved. Different microbes may become resistant to the antibiotics, and these resistant microbes can then infect not only the fish in cage but also the local macrofaunal communities, altering the species landscape (Yoza *et al.* 2007).

Therapeutants (malachite green, formalin) are also used to treat fish diseases. Again since these are not enclosed ponds these agents are added to the feed for efficient delivery. These are harsh chemicals which help prevent diseases, but as with antibiotics can alter the species composition of the local ecosystem near the cage. There is often concern among local communities that the fish cages are harbors for disease which can then escape and impact the local species. Studies from British Columbia have associated the increased incidence of sea-lice in wild salmon populations to the influx of offshore ponds (Shaw et al.). These studies also indicate a proximity effect of these cages to spawning grounds as having an effect on the spread of the sea-lice (Willis *et al.* 2005).

Antifouling chemicals (most often toxic metals) have been used on ships for decades. Because of this build-up cages have to be scrubbed clean by divers on a regular basis. This scrubbing action (and the wearing action of the oceanic water itself) breaks up and dissolves these toxic metals and releases them into the environment. These pieces settle to the bottom or are dissolved and enter the water column, where they too can alter the species composition of the local microfauna (Graslund and Bengtsson 2001).

Genetics

Genetics are a relatively narrow topic of impact. Farmed fish are either a) a different (non native) species, or b) a local species that is not as 'fit' as the wild variant. This introduction of organisms often forms the basis of local community opposition to aquaculture development in an area.

Fish escapes occur either when transferring the fry to the cages or when harvesting, or simply when there is an equipment failure overnight and the hole in the cage cannot be fixed immediately. In situation a) above, if the fish is not a native, then several outcomes may occur. Either the fish will not be able to compete with the native species in the new environment, or, the fish (a gravid female or several fish) will be able to occupy an underused ecological niche or outcompete a native species and become established. The establishment of a non-native species often involves negative impacts such as the displacement of a less 'fit' native species which cannot compete, or in extreme case cause the disruption of the entire ecosystem.

If the fish is a native species, then the potential harm of a release is lessened. There are no concerns about a non-native species taking over. However, cultured native species are born in hatcheries. As hatchery science improves, the fish are being bred for traits that are preferable to the farmers, i.e. fast growth, later sexual maturity, and docility. These are often the exact traits selected against in wild populations. By allowing for escapes and potential interbreeding with their wilder brethren, the overall genetic fitness of the species declines. Therefore, when an invasive species arises or environmental climate changes these fish with decreased fitness will be less able to adapt and compete and may be completely wiped out.

Use Conflicts

As the human population increases, coastal communities have also grown to the point that in 1995 a full 39% of the world human population was living within 100km of a coastline

(CIESIN *et al.* 2000). This has also increased the ecological pressures on the local shorelines and waters. From heavy industry to sewage plants to tourism, the demands placed on the coastal waters are ever increasing.

Hawai'i lacks heavy industry; hence the primary private economic support is high level of tourism. Tourism is a well established industry in most places around the world. Many of the same environmental features that make an ecosystem pleasing to the eye are also the same features that make it suitable for aquaculture (well serviced via infrastructure, clean waters). This has led to conflicts, which have had to be resolved via the court system. There are numerous examples from Europe (and British Columbia) where the local and national tourist boards have filed lawsuits to prevent aquaculture from developing in an area because it would impact their business (da Silva 1995, Hamouda *et al.* 2005). Tourists are often averse to fish farm operations, which they see as a blight on the natural beauty of an area. Since the tourism boards in many of these areas, such as Italy are so powerful, the courts often side with them and prevent the development of aquaculture in those areas (Read and Fernandes 2003). In Hawai'i, the potential conflicts occur with several user groups, namely aquatic sports and tour boat operators. There are also the environmental groups that oppose any change to the natural environmental, fishermen, and native rights / sovereignty groups.

The aquatic sports, fishermen, and tour boat operators have direct conflict with aquaculture operations due to their use of the waters. If the waters are used for aquaculture, they cannot directly be used for any of these activities (the farm operators often have exclusive use clauses written into the lease that bar divers from the area). This results in a situation of 'better use' of a resource, with the question of which operation is better for the overall economic survival of the state in the long run? The answer revolves around the type of aquaculture, its management and business strategy. Often though, short-term economic realities predominate, tourism will appear better for the state and hence aquaculture will be disallowed.

For the environmental groups, most are pure preservationists, and hence any manmade or pollution causing venture will be opposed. Consequently, aquaculture, even in its most advanced and sustainable form will be viewed as a threat to the natural balance of the local ecosystems, and will be treated as such via lawsuits and protests.

Native Hawaiian advocates argue that the use of the oceans is limited to operations that meet with their approval. Under the ceded lands concept, all oceanic environments (benthic and the water column itself) belong to the Hawaiian people. Their uses of the lands/waters include traditional fishing and gathering practices, which can conflict with the 'exclusive use' clauses mentioned previously. This is a harder issue to resolve and though the case was ruled upon by the US Supreme Court, it is still being decided in legislation (Office of Hawaiian Affairs 2009).

Offshore aquaculture is generally considered more sustainable than the 'traditional' 5-year fishpond in a mangrove model previously practiced in the Philippines and Thailand (Barbier *et al.* 2002, Primavera 1997, Paw and Chua 1991). These short term ponds have had devastating results; even after their closure there still are issues with pollution and newly identified land loss due to sea encroachment via a loss of mangroves (Al Jazeera 2009). Several solutions must be applied in parallel to address properly these issues including sustainable management and farming practices, and proper siting.

Siting Mitigation

There are numerous models from all over the world that have attempted to assist with the proper siting of offshore aquaculture facilities. Most notable are the regional scale Multi-criteria Decision Making (MCDM) models: the LENKA system from Norway, Scotland and BC, all three of which are all based on salmon farming.

Scotland uses a zoning system based on guidelines for fish habitat, and is more qualitative(Levings *et al.* 1995). Some of these guidelines include distances from other industries, 8km between farms, 0.5km from fishing grounds, shellfish 3.78km from fish farms. Farms larger than 6km^2 require an EIS. Identification of "sensitive areas" (areas with 'other' interests, not fish habitats), knowledge of environmental conditions such as temperature, salinity, Dissolved Oxygen (DO), currents, and runoff. Into this physical data mix the Scots use a referral system between government offices (such as their equivalent of the Hawaii Department of Agriculture and the Department of Land and Natural Resource Management) to identify if a particular area is suitable for a farm. There is no concern for proximity to wild salmon (Ross *et al.* 1993, Read and Fernandes 2003).

Ireland uses administrative guidelines whereby areas must be designated by the Irish Fisheries Act. No farms are to be placed in bays with low current velocity (80% current<0.1m/s). Additionally, an EIS is required for farms with production of 1000t/year.

Again, there is no distance requirement from wild salmon (Read and Fernandes 2003, Stewart 1998).

Iceland focuses solely on distance from rivers with wild salmon, whereby depending on the size of the farm it must be between 5 and 15 km away from the mouth of the river (Levings et al. 1995).

Norway created the national model LENKA (nationwide analysis of the suitability of the Norwegian coast and watercourses for aquaculture) system (Kryvi *et al.* 1991). The LENKA is a broad scoped, semi quantitative model which focuses on the carrying capacity of the waters based on predicted production. It is scale limited to 1km resolution, so it is used for wide-range planning and not individual farm sites. Include in the considerations are effects on wild salmon, water quality, health of farmed fish, pollution effect on marketability, water quality, temp(low temps), ice cover, exposure (high wave heights)/currents (limited data were initially available), and infrastructure. Across Norway, 600 LENKA zones were identified. It is used to guide aquaculture to appropriate areas with minimal impact (natural and self-polluting). LENKA set a minimum depth of 20m, as well as minimum distance above benthos of 10m. Three zones were created A, B, C, with A being more appropriate than B and C being off limits. There is an inclusion of 'salmon protection zones' (mouth of salmon river to 6km out) in the model (Kryvi et al. 1991).

British Columbia, Canada is home to some of the largest farm operations outside Norway. Their system, also semi-quantitative, consists of biophysical criteria which rate sites for effects of environment on cultured fish (physiological effect, ecological, and engineering requirements) (Berris 1997). Overall, 12 factors were considered and the areas were rated as good, medium or, poor. Unlike LENKA there was consideration of infrastructure or economic factors. This was also a static model that has no allowance for mitigation techniques or technological improvements. Coastal Resource Interest Studies (CRIS) used to zone areas (a qualitative rating) using discussion and negations between agencies. There must also be 3km distance between farms, with development plans for farms filed before production. To account for the impacts of escaped fish the system uses a 1km distance from major streams, 3km from rivers, 1km from herring grounds, 100m from shellfish beds (Berris 1997).

All these systems address the problems from one or two facets, and none is a complete system or provides all the answers to a region's or nation's facility siting problem. Consequently, there is room for the development of new models which address site suitability in different ways and for different regions.

For water quality, proper siting is essential. If placed in an area with poor or low water exchange, the farm operation will self pollute, destroying itself and the local environment. Additionally if placed too close to a river or effluent from a point source, the original water quality will be poor and hence affect the health and overall quality of the fish. A properly sited cage will have sufficient water exchange (via currents) to disperse and dilute the wastes before they have a chance to effect the ecosystem. However, it cannot be in an area with too rapid currents as then the fish will have to work harder (not grow as fat) and feed will be lost before they have a chance to eat it (wasteful for the farmer and detrimental for the benthos downstream). The LENKA and BC systems work well for addressing water quality as they focus on carrying capacities of the local waters (Berris 1997, Kryvi et al. 1991).

For the benthos, proper siting can have significant impacts. Poorly sited operations will alter the ecosystem of the benthos beneath the cages (currents are a major factor in this as well). This can lead to lasting effects such as the creation of microbial mats where none-existed before. Properly sited and properly managed cages will have negligible impact on their benthic communities. All the LENKA, BC and Scotland models deal sufficiently well with this aspect of the environmental effects (Kryvi et al. 1991, Berris 1997, Ross et al. 1993).

Chemotherapeutics are more of an issue for proper management. If the operator overfeeds and wastefully applies antibiotics and therapeutants to the feed, or improperly scrubs the cages so that the toxic paints are washed away, then the local environment may suffer. However where siting does have an impact is in the choice of an area with proper currents and water exchange (as with the above two). If a farm is sited in an area with sufficient current to minimize the concentrations of any of these additives, then their overall effect will be negligible. Additionally, the farmer and government has to ensure that the farms are not placed in high densities, as the effects of these chemicals is cumulative. Hence, one farm might have negligible impact, but 4-5 farms over tax the local capacity of the ecosystem to dilute the toxic effects leading to ecological disruptions. LENKA is the only system that directly considers the health of the farmed fish in its model (Kryvi et al. 1991). The other models address this issue partially by considering chemotherapeutants wastes.

The issue of genetics can be difficult to address via siting. Again, this is a management issue. Genetics can be most easily addressed by considering cage distance from various variables such as other cages and native fish spawning areas. Though fish swim and are capable of covering large distances, if the cages are placed far enough away from the native habitats of the wild stock, then the effects of an escapee should be minimized. Placing a cage directly at the mouth of a spawning river, or on a spawning ground is detrimental to both the farm and the local ecosystem. Scotland is the only system detailed above that does not consider proximity to wild-stock an issue (Ross et al. 1993). The rest of the systems deal fairly well with such proximity issues to wild stocks of fish (Levings et al. 1995).

User conflicts are possibly best addressed with siting. The ability to identify places that are used for other purposes, (and to be able to put an economic value on those uses), allows the manager (State and farm) to search places which have minimal conflicting uses. If no such pristine areas are available, then the manager can identify areas where the current use is less than fiscally or even environmentally optimal. Scotland and LENKA, and BC each deal relatively well with user conflicts of a fiscal nature. BC incorporates first nations (tribal) considerations into their methodology. This would be vitally important for Hawai'i. Native Hawaiian claims to ceded lands, as mentioned previously, continue to be a contentious issue, particularly with future expansion of the local aquaculture industry. Kona Blue Water Farms, well known for their outreach to local community and native groups during their planning stages, has encountered legal resistance from native groups for their planned expansion (Gomez 2009). Consequently, proper siting is vitally important as it allows users to identify areas that are viable for use and others that should be held in reserve for alternative social uses such as traditional practices, and general recreation.

A properly sited farm operation can mitigate if not avoid entirely many of the environmental (and social) issues associated with it. Farms that are sited poorly will eventually fail due to their self-pollution or lack of economic viability. A properly sited farm will have sufficient water flow rates to avoid both water column pollution and benthic problems because the wastes and feeds will be diluted and dispersed (and even the impacts of the chemotherapeutants will be negligible). It will be located far enough away from sensitive habitats (spawning grounds) that genetic contamination of the local stocks will be minimized. It will also be located in areas where there are few alternative users, so conflicts with scuba diver and whale watchers will not happen. In addition, it will be on grounds where the native population has minimal interests or even better supports the development as a viable revenue stream for the community.

Modern Site Suitability

As was described in the previous section, the use of GIS as a tool in decision support systems has increased (Kapetsky and Aguilar-Manjarrez 2007). The prevalence of GIS in many facets of science and management makes it the logical choice to incorporate and present data (da Silva 1995). Through this increased utilization, most coastal models around the world have remained focused primarily on one of three main areas. Previous models have been environmentally or economically and socially based (Kapetsky and Aguilar-Manjarrez 2007). Very few of these models have attempted to integrate the three disparate areas of concern. Other than the regional models mentioned above, most GIS based models for siting of offshore aquaculture facilities have focused on relatively small local geographic areas that have been well studies and have abundant information (Radiarta *et al.* 2008). The use of GIS at regional scale for site selection is problematic due to the dearth of detailed fine scale data for marine environments. Regional scale MCDM programs are best suited for site suitability determinations.

It is the contention of this study that there is a minimum input set of knowledge that can be utilized in any situation regardless of cultural background, technique, location, and species (Arnold *et al.* 2000). By utilizing this simplified framework, offshore aquaculture can avoid the pitfalls that plagued the early land-based aquaculture in the late 20th century, such as unsustainable environmental practices and cultural insensitivity. A minimal dataset model based on publically available data will also allow for regional scale implementation as most coastal regions have some coarse marine data. The smaller the dataset needed for the model, the more widespread its application. The results from the minimal dataset will allow users to identify areas in which can target then be the focus of more expensive and detailed data gathering from which a proper site selection decision can be based. With its rich historical background, Hawaiʻi is the perfect test area for this minimal dataset based framework.

Chapter 4 Site Suitability and GIS

Since the dawn of aquaculture, site selection has been an important factor in the success or failure of the operations. The core requirements of environmental and economic limits have been consistently present, though the consideration given to each has varied widely, and with dramatic repercussions for environmental stability and farm sustainability. Due to early limits in technology, site suitability models were limited to land based operations. As GIS is dependent on the quality of data utilized, until recently there simply was not enough robust data available to produce a viable analysis. This technological limitation is doubly true for marine environments (Helsley and Umemoto 2003). Offshore information is consistently more expensive to collect, complex to interpret, and of such large size that it was not until computing technology reached the early 2000s that offshore site suitability began to be studied in earnest.

Permitting

The permitting process in Hawai‘i involves a mix of governmental institutions at the federal state and county levels. Though this process has been streamlined in the past decade (Hawaii Aquaculture Development Program 2009) it still represents a significant investment by interested parties (Young 2008). Three levels of government require permits, federal, state, county, and each must be addressed in turn. Though these permits are intended for terrestrially based fishponds, the procedures and permits remain consistent, with the addition of applying for an offshore lease for floating cage cultures.

The federal permitting guidelines were restructured and streamlined after the year 2000 in an attempt to increase aquaculture development. Prospective producers must receive permits from the department of the Army, address the Clean Water Act (Section 404), provide a historic site review (Section 106), receive a review from the U.S. Fish and Wildlife Service as well as the National Marine Fisheries Service, and provide a Coastal Zone Management Consistency Statement (Farber et al. 1997, Keala et al. 2007).

The State of Hawaii's main department of contact for coastal development projects is the Department of Land and Natural Resources (DLNR). Consequently, many of the permits are coordinated through their office. These permits include: Conservation District Use Permits, an EIS or EA (as required by Hawaii Revised Statute 345), coordination with the Coastal Zone Management Program, water quality certification from the Department of Health (Hawai'i Revised Statutes (HRS) § 401), and conditional requirement from the State Historical Preservation Office ,for identified Hawaiian fishpond restoration projects (Farber et al. 1997, Keala et al. 2007). These permits often take several years to obtain and signify a significant investment in time and funds.

At the county level, there are fewer permits. These permits include a Shoreline Management Area Permit, a Shoreline Setback Variance (in the form of a survey), and Grading Grubbing and Stockpiling Permit (for shore-based ponds as well as for shore-based support facilities). If the project aims to use a state-owned fishpond, there are additional permits required before operations can begin. These additional permits are coordinated with the DLNR , and include, DLNR–Land Management Divisions State lease (also needed for offshore cage locations), evidence of Nonprofit (501 or 501c) status, metes and bounds survey and land appraisal, lease rent negotiations, Right of Entry Permit, insurance coverage, and a building Permit (Farber et al. 1997, Keala et al. 2007). This list of permits represents a substantial barrier to entry for interested aquaculturalists. Though efforts have been made to streamline the process on a local level, little effective progress has been made in removing the overlapping nature of the permits (Keala et al. 2007).

GIS and Aquaculture

Development of modern site suitability protocol for aquaculture began in 1993 (Ross et al. 1993), and 1994 (Hajek and Boyd 1994, Silvert 1994, da Silva 1995). Though contemporary versions have included island habitats as locations for aquaculture site suitability protocol (Yokoyama 2003), none has been focused on Hawaiʻi. Nor have the previous island studies incorporated local historical and cultural knowledge. The few previous studies on site suitability which incorporated cultural information where primarily based on bivalve species (Arnold et al. 2000).

Hawaiʻi was the first state to have a comprehensive aquaculture plan in 1979 (Corbin 2007). Site suitability was originally focused on land based pond culture technologies. The original work was done via analog paper map overlays. With the advent of computers and digitization Hawaii's information went digital. The state has proposed that the next update of its aquaculture plan would be based on GIS using highly accurate digital information (Corbin 2007). Even though, modern studies on aquacultural site suitability involving GIS were begun in the early parts of the decade (Young et al. 2003), continued work has stalled.

The desire to optimize marine site suitability using GIS dates back to the late 1980s. Kapetsky (1989) conducted a study analyzing siting criteria for both land-based shrimp ponds and floating fish cages in Malaysia. His groundbreaking work included analysis of wind, waves, currents and bathymetry. The initial analysis and criteria for inclusion came from studying pre-existing operations. The outcomes of the study however provided definitive reasoning for the geographic site suitability of the extant operations. The author recommended that all possible information regarding existing sites, including conversations with managers be gathered before new framework developments, as this provides the most robust and accurate data, thus increasing the predictive capacity of the model (Kapetsky 1989).

By 1993, state of computing capabilities had evolved so that more complex data could be used. Ross *et al.* (1993) included water quality in their site suitability criteria for salmonid culture along the coast of Scotland. By utilizing the novel approach of overlaying successive layers of data, the researchers produced maps that indicated potential sites that were suitable for floating cage culture, based on bathymetry, currents, waves and water quality. Of the total area studied a mere 6.4% was identified as fitting the environmental requirements for cage culture. The authors also noted that standard methodologies are good for general site suitability; however, specific areas should be treated on a case-by-case basis. This study, like so much of the early work in GIS based site suitability, focused solely on environmental criteria, and did not include any social or economic concerns (Ross et al. 1993).

It was not until almost a decade later that the next major study of GIS for marine aquaculture was published. Aguilar-Manjarrez (1996) utilized numerous inputs for developing and testing a broad-scale GIS decision support system in Mexico. The study incorporated alternative land uses, environmental conditions, social impacts, production considerations, and economic conditions into the models (Aguilar-Manjarrez 1996). Perez *et al.* (2002) analyzed water quality requirements for site suitability in the Canary Islands. This more detailed study of water quality requirements included pH, dissolved oxygen (DO), turbidity as well as temperature. This study utilized both data overlay methods previously established by Ross *et al.* (1993), as well as Multi Criteria Evaluation (MCE) techniques to arrive at the final product. The authors observed that MCE became unwieldy with over 10 criteria, hence they recommended that the evaluations be subdivided into smaller groups, whose outputs are then combined (Perez *et al.* 2002, Ross 1998).

Kapetsky *et al.* (2007) described three classes of information, which are required for viable marine aquaculture projects:

- Biological suitability of the environment for the target species;
- Environmental suitability for the chosen technology;
- Access; which includes government jurisdictions, competing uses for the water column and bottom as well as land for siting an on-shore facility.

By investigating fish, bivalve and marine plant culture, the authors showed that the general procedures for site suitability are standard, regardless of the species produced. Kapetsky *et al.* (2007) also were among the first to utilize publically available data sources to increase the general access of their model and to keep costs at a minimum. Remote sensing of data was considered as a viable input into the decision model, however, due to high costs, it was not included as a vital portion. The authors used their system to address competing uses for limited offshore areas.

Recent GIS work for siting aquaculture has continued to focus on the biophysical requirements and economic limitations of site suitability (Radiarta et al. 2008). These models continue to incorporate large numbers of complicated layers as well as custom collected data. Though this makes these models more robust, their complexity increases the amount of time needed to obtain a result, and are not well suited for preliminary decision making. The model used by Radiarta *et al.* (2008) also does not include traditional uses of the area and thus is not a complete model that is suitable for locations with a strong traditional use community structure, such as the Pacific Islands.

Social Impacts of Aquacultural Development on Coastal Communities

The growth of aquaculture has brought with it a many changes, not only environmental, but also economic and social to the coastal communities where it has been introduced. Often times there have been disputes regarding traditional uses of the "common" property, such as fishing, and the new closed privatization of those same areas. This contentious issue becomes more complex with the incorporation of indigenous communities interests in these same areas. As is often the case with the introduction of a new technology, the laws that regulate that technology lag behind its introduction and are often created retroactively from the initial disputes in the communities where the technology was introduced.

Numerous social issues have developed with the advent of modern aquaculture. Most of them revolve around the issue of fishing rights and access. In the modern sense, the concept of common property has shifted (Schlager and Ostrom 1992). Common property resources have differing definitions in the literature, some of which include:

- Property owned by the government;
- Property owned by no one;
- Property owned and defended by a community of resources users;
- Any common-pool resources used by multiple individuals regardless of the type of property rights involved.

Often in the literature the terms: open-access and common property systems are used interchangeably. Shlager and Ostron (1992) attempted to standardize the definition of a right as referring to a particular action that has been authorized. Consequently, a property right is the authority to undertake particular actions related to a specific domain. Additionally, all rights have complimentary duties associated with them. The distinction between rights at an operational-level and rights at a collective-choice level is crucial. It is the difference between exercising a right and participating in the definition of those future rights to be exercised. Consequently, rights place a duty on compliance by others, therefore one must turn to cultural norms, and external enforcement to achieve enforcement of those rights (Schlager and Ostrom 1992).

In Hawaiʻi, native rights and access have been a contentious issues for many years. Beginning with the Great *Māhele* in 1848, land rights and access to resources have been a point of contention (Chinen 1958). In 1993, the Public Access Shoreline Hawaiʻi (PASH) decision re-affirmed Native Hawaiian rights to access and observe traditional practices. As in other places, the growth of offshore aquaculture, (and their onshore support facilities) in Hawaiʻi will lead to resource use conflicts with local and native communities. By incorporating this social aspect into the site suitability framework, it is believed that large disagreements may be averted.

Chapter 5 Methods

The modern development of aquaculture, particularly marine aquaculture, faces significant hurdles. Conflicts arise because mariculture facilities require similar coastal resources as those that are desired by recreation, tourism and rural lifestyle (Anutha and Johnson 1997), including:

- Proximity to major urban centers and infrastructure;
- Clean waters;
- Easy access between land and water;
- Relatively stable environmental parameters such as weather and tides;
- Long-term and exclusive use of public lands, potentially impinging on other community uses of the area.

These conflicts can stall or even prevent aquacultural development in an area. GIS and Multi-Criteria Decision Making (MCDM) tools can be helpful in resolving these conflicts and act as aids in fostering constructive discussions between varying stakeholders. To date, the use of GIS in aquaculture has assisted primarily in site suitability and site selection of land-based production systems (Helsley and Umemoto 2003). The framework developed in the course of this project is designed for site suitability analysis; this limits the scale to a regional outlook. The output from this framework is not geared for individual site selection at a local scale and does not indicate exact locations for farm operations. Instead the regional scope of this framework identifies general areas which are suitable for further detailed research, thus saving the interested parties time and money in detailed research of areas which are not suitable for offshore aquaculture.

The process for site suitability of aquacultural areas is analogous to site suitability protocols in many other developments in that a substantial portion of time is devoted to pre-analysis. During this initial phase, all potential data sources are gathered and examined for utility to the current task. Because this project utilized a minimal dataset approach, a rigorous selection process was employed to limit the data layers to only those that have the greatest impact on the model. As with other GIS projects, without the inclusion of a minimal dataset restriction, data layers, (and their associated costs) could have grown exponentially. After the initial phase, the viable data were entered into a simple model space within the GIS program and various scenarios were applied. These scenarios were then compared with each other and any existing production sites for verification.

GIS

Through the use of GIS and established source information, a simplified weighted model was established which can be utilized by interested parties to identify potential sites for aquaculture expansion. This particular framework is robust enough to be adapted to any finfish species and other culture technologies in locations outside of Hawai'i. Several simple steps were developed which allow for the creation of this limited dataset model:

- *Step 1*: Identify and gather pertinent updated GIS data available through State and University sources. This includes environmental and political data.
- *Step 2*: Break the framework into four distinct sub-protocols:

1. Basic: This is the first step in identifying areas deemed as prohibited for use by State and Federal exclusion zones, as well as pre-existing structures. All subsequent examination of acceptable areas will be determined from the output of this category.
2. Enviro-Biological: Identification of areas based strictly on the physical limitations of the culture technology.
3. Economic: Site suitability based solely on the economic variables associated with offshore cage culture, such as infrastructure, which can be geospatially addressed.
4. Socio-Political: Site suitability based on the constraints associated with competing uses (such as recreation) and of native Hawaiian interests.

- *Step 3*: Re-Combine the above subsections into a unified MCDM, to identify viable areas.
- *Step 4*: Scenario Comparison and model verification: Determine if different buffer distances, and the inclusion of military zones (non-publically released data) affect site location. Confirm that existing aquaculture developments appear within predicted areas.

Data were gathered from various sources (online, intranet and traditional paper publications) within the State of Hawaiʻi and federal systems and the University of Hawaiʻi. Through Dr. Leonard Young at the State of Hawaiʻi Aquaculture Development Office, access was granted to all previous works and sources including GIS data acknowledged as residing on the State of Hawaii's intranet database, but not released to the public.

The methodology followed the standard GIS analysis techniques, outlined in Hadley *et al.* (2003), and those used by the FAO (Aguilar-Manjarrez and Nath 1998, Kapetsky and Aguilar-Manjarrez 2007). As mentioned previously, the purpose of this framework development was to create an inexpensive and simple to use general framework that can be utilized in a multitude of locations. Following the FAO methods, publicly available data were used to maximize cost-efficiency and ensure product transferability.

There are several methods available for optimization of GIS layer analysis; the most frequently used and easily transferable are Weighted Linear Combination (WLC), and Boolean operation (Kapetsky and Aguilar-Manjarrez 2007). In WLC, criteria are standardized and integrated using a weighted average. By manipulating the assigned averages, the final output can be changed to identify different areas (Kapetsky and Aguilar-Manjarrez 2007). Boolean operations are a system by which the criteria are equated to logical statements and then combined using traditional logical operators (AND, OR) to create a suitability map (Kapetsky and Aguilar-Manjarrez 2007). As neither of these systems was determined sufficient on its own, the framework employs a hybrid system whereby Boolean operators were used to create the individual layers and the scenarios. The final overlay combination was completed using a simplified WLC with all individual components retaining equal value weight within the model. As there was a lack of publically available information on local preferences regarding aquaculture, different weights were not employed in the output of the model. In order to determine complete model functionality, a sensitivity analysis was also completed which allowed for a greater weighing of individual factors.

In this minimal dataset model, use conflicts were resolved *a priori* by using published literature. This data mining allowed for the inclusion within the model of only the most pertinent of data, thus avoiding the potential disagreements generated by inclusion of divergent preferences. Often the resources which can become contentious issues are not included in publically available data and thus would not be addressed by a minimal dataset model based on publically available data. Consequently, the weights of the various data became black and white issues that were compared in the various scenarios, further simplifying the model and ensuring both its robustness and transferability.

The original Hawaiian model (Helsley and Umemoto 2003) included of bathymetry, restricted areas, water classifications, and three-mile boundaries. It was the intention of this framework to retain the simplicity evidenced in the Helsley and Umemoto (2003) model, but to utilize more up-to-date information and reformulate several important factors concerning the restricted areas by incorporating Native Hawaiian social concerns and economics.

Data collection consisted of gathering pre-existing freely available data from public sources such as the State of Hawaii's Aquaculture Development Program Phase 1 site selection results (Helsley and Umemoto 2003, Young et al. 2003), University of Hawai'i Urban and Regional Planning Program (DURP), and previously published economic results (Leung 2007, Ziemann 2004, Kam et al. 2003, Friedlander and Ziemann 2003, Leung et al. 2002, Kam *et al.* 2002). DURP has numerous internal and historical publications, which specialize in native

Hawaiian development issues. These internally created professional grade publications (practicums) are public documents that are available at Hamilton Library at the University of Hawai'i at Mānoa. These practicums are created by groups of graduate students in DURP under the oversight of a faculty member and primarily meet the requirements of public (non-UH associated) clients. Some information which was identified through the use of DURP were native Hawaiian definitions of a*hupua'a*, as well as historical boundaries of *kapu* (forbidden), and *konohiki* (community managed) fishing areas.

Other sources of data included the Environmental Assessments filed by Kona-Blue and Cates International with the State of Hawai'i. Preliminary conversations with private parties such as aquaculture operators on the islands of O'ahu and Hawai'i were conducted to supplement information obtained from the publicly available published sources. In this current GIS analysis, traditional descriptions of Native Hawaiian interests were preferred to new interviews on the topic of traditional uses. New interviews would reflect newly gathered and published information on current uses (which were already included in the model). Older published sources reflect historical usage of areas and thus allow for a preservation of anthropologically important areas. Within the published descriptions of Native Hawaiian interests, maps were particularly useful due to the ease of transferring such information into GIS data layers. Next in usefulness were geographical descriptions of areas such as those found in Kosaki (1954).

Parameters

Before any work could be completed in developing the model, the universal parameters were established. This analysis focused on the three mile boundary around the island of O‘ahu, because this is the area over which the State and County of Oahu have direct control (Figure 7). Other islands were not included for several reasons:

- Competing publically funded projects being produced concurrently in Hawaii County and the proposed State of Hawai‘i project around Maui County.
- The majority of Kauai is located within a Military zone, which is incompatible with aquaculture.

For the model to be transferable the data must be converted to raster format to be compatible with the final WLC analysis. A standard cell size of 100 m^2 was established. This cell size was determined appropriate after considering the minimum size of current operation around O‘ahu of 11.3 ha and consideration of future operations; this provided a rough average and was in line with the simplified basis for the model.

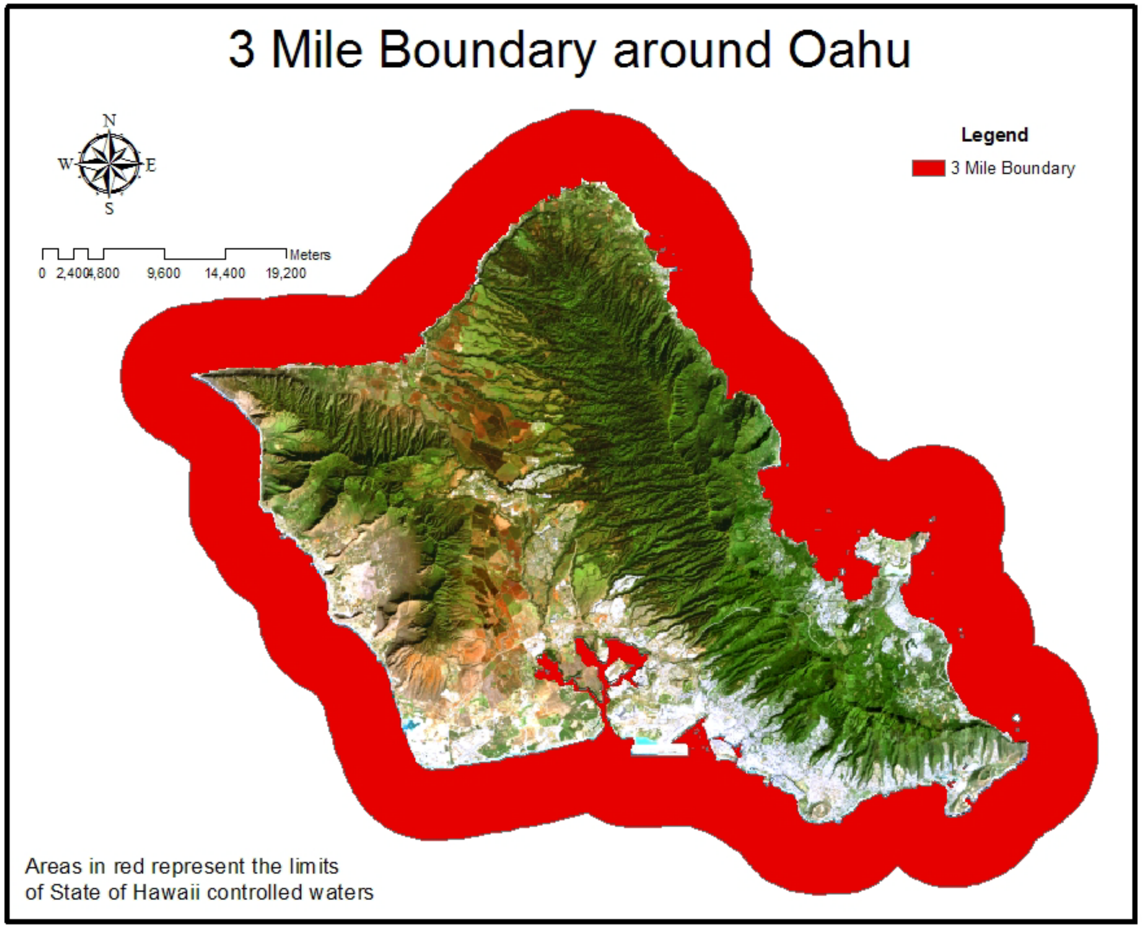

Figure 7 3 Mile boundary around O'ahu designating State of Hawai'i controlled waters

Smaller cell sizes significantly increase the amount of storage and computer analysis time needed beyond what is reasonable using today's equipment (Intel Core 2 Duo™ 2.4 Ghz, 2 Gb RAM, 300Gb Hard drive) without a corresponding increase in resolution results. As this is a regional scaled model for site suitability, there was no need to deliver resolutions smaller than 100 m^2. The use of a 1 ha cell allowed for standardization between the data of different resolutions. Most data were provided in polygon format; however, some data were point based in which case a buffer had to be applied to create a polygon that could be converted to raster format. The size of the buffer was determined by using Hawai'i Revised Statutes (HRS), and literature searches on potential restrictions associated with the objects. Additionally, bathymetry data was also d in point format, consequently natural neighbor interpolation of the data was used to fill gaps. Wholesale conversion of point data to polygons with interpolation was not conducted as this introduced a level of uncertainty that was not beneficial to the minimal dataset model.

The first objective was to identify all the potential datasets that were publically available. Of the multiple data that are available, the marine and infrastructure layers were considered most important for inclusion in the model. Though some demographic layers such as population and Tax Map Key (TMK) can be important in the consideration of aquaculture siting, they are not the most vital to consider in the initial site suitability and are better suited for second tier analysis. The layers which were considered for inclusion are shown in Table 2.

Table 2 Available data considered for inclusion in the minimal dataset model

Marine	**Infrastructure**	**Social**
Bathymetry	Harbors	Recreation Zones
Bottom Type	Road Networks	Socially / Culturally Important Sites
Fish Management Areas	Airports	Military Zones
Fish Aggregating Devices		TMK
Obstructions		Population
Sewers		
Cables		
Buoys & Navigational Aids		
Marine Protected Areas		
Wrecks		
Dumping Areas		
Waves		
Currents		
Water Classification		

Following a Boolean operation using the available layers, the second objective identified areas that are unacceptable for any form of development or private use as determined by State and Federal Regulations. The State of Hawai'i Department of Health HRS Title 11, Chapter 54 Water Quality Standards (State of Hawaii 2004) delineates the coastal waters into classes, A and AA. Phase 1 of the Hawai'i ADP site selection project (Helsley and Umemoto 2003) previously determined Class A and AA water in Hawai'i. After discussions with the State aquaculture specialist who conducted the original Phase 1 site selection project (Young 2008), the future of the water classification system is in doubt. Consequently, this information was not included in this framework. Additional political-based layers which were included are Marine Life Conservation Districts (MLCD) and Marine Management Areas (MMA). The end result was a new map which delineated the Hawaiian waters into areas in which there is no possibility for aquacultural development, and zones in which there is potential. It is this basic layer upon which the following simplified WLC is employed.

The third objective was to divide the available data into Enviro-Biological, Economic, and Socio-Political components. Experience has shown that multiple criterion analysis decreases in efficiency when more than 10 factors are considered simultaneously (Aguilar-Manjarrez and Nath 1998). Dividing the framework into subcomponents does facilitate understanding and acceptance among the various interested parties in the final product. Subsets should be created when the number of data layers in a particular subsection exceeds 10. Because of the minimal dataset concept, no individual focus layer (economic, environmental or social) had more than 10 individual data layers, consequently subsets were not required. The output generated from these components was next combined into an overarching weighted protocol equation.

The FAO utilize a robust four-tiered system to describe an area's suitability for aquacultural development (Aguilar-Manjarrez and Nath 1998). The four groups are: Very Suitable: "minimum time or investment is required in order to develop fish farming"; Suitable: "modest time and investment are required"; Moderately Suitable: "significant interventions may be required before fish farming operations can be conducted"; Unsuitable: "either time or cost, or both, are too great to be worthwhile for fish farming" (Aguilar-Manjarrez and Nath 1998). This system was originally developed for terrestrial aquaculture operations with complex, multi-layer and well studied GIS datasets. After careful consideration it was determined that this system was not appropriate in a minimal dataset framework. A more simplified version of site suitability categories was applied to the minimal dataset model and included Very Suitable, Suitable, and Moderately Suitable. Due to the initial identification of sites which are incompatible with offshore aquaculture, the Unsuitable category was not applied within the model.

The standard software used was ESRI's ArcGIS package; newer versions (v9+) of this software do not have the research community's input in terms of add-on packages (as opposed to the earlier v3). These add-ons do not work within the new v9+ architecture, thus potentially viable pre-existing site suitability or site selection modeling codes were not usable. ArcGIS 9.1/9.2 (ESRI 2007) was utilized as the software is readily available and considered standard.

As this is a framework based on a minimal dataset, the outcome is based on both Boolean operations as well as WLC equations. The primary equations and scenario were determined using Boolean operators of 'AND' and 'OR,' while the final predictive model was based on the following the simple WLC formula presented below, where *x* is the weight determined via the particular scenario, *data* is the publicly available data layer, and *output* is the resulting GIS data layer.

$$Output = \Sigma(([data_1]x_1) +....+ ([data_n]x_n)$$

Since all data layers within a particular equation had equal weights, a weight of 0.5 was used.

Basic and Military Constraints

This is the first level or filter through which the publicly available GIS data were applied. Using a different set of data and model-space, similar go/no-go areas have been previously determined in Phase 1 of the Hawai'i ADP site selection program (Helsley and Umemoto 2003). As new and different data were available, this basic map was recreated for this project. The resulting output is GIS data for the waters around O'ahu. All the layers and area in consideration were within the state-controlled three-mile boundary. As per the EA provided by Kona Blue, all sites have a 30m buffer (unless specified otherwise) to allow for water quality to return to ambient levels (Kona Blue Water Farms 2003). Contrary to minimal dataset procedure used in the proceeding sections of the model, the Basic layer should be populated with as much data as is applicable. For this reason, the Boolean operator "AND" was used within the GIS model-space to create these layers. The reason for this comprehensive data inclusion is the need to identify all potential variables and areas which are strictly incompatible with aquacultural development. To qualify as incompatible a site must have a pre-existing designated use or protection (such as sewage lines, undersea cables, wrecks or coral reefs and other protected zones). In addition to the Basic constraints, The State of Hawai'i has data layers which contain areas reserved exclusively for military use. These data layers are not made available to the general public but were made available for this project. Individual details of the military layers are not divulged herein; rather all the areas are simply addressed as an additional constraint layer on top of the Basic constraint.

These are all areas that would restrict concurrent use with aquaculture. This resultant data were then used as the basis for the following analysis.

Basic = Σ([private_sites] AND [public_protected_sites])

Military = Σ([private_sites] AND [public_protected_sites] AND [military_reserved])

Environmental

These are a set of considerations based solely on the physical limitations of the culture technology. During this site suitability model, all areas are assumed to be capable of being within the physiological limits of the animal (e.g. temperature, optimal depth, currents, turbidity and salinity). These important considerations for a site's capability of housing and growing animals must be addressed in the follow-up site selection model proposed at the end of this dissertation.

The new culture cages are constructed to robust specifications which can tolerate strong currents and physical stresses such as category 4 hurricanes. However, maximum depth for anchoring and maintenance needs to be considered. Though the technology can be anchored in very deep areas, there is a substantial cost associated with material and maintenance of such a site. The state of the art anchored offshore cages must be placed in at least 25m of water (to qualify as offshore); they can be tethered to vertical walls or muddy bottoms and anything in between. The cages should withstand category 4 hurricane winds (241 km/h), currents up to 2.5 knots, and a storm surge 6m above normal (Ocean Spar 2009b).

The first step in identifying the minimal dataset environmental parameters was to understand that the species is of less importance than the culture technology (Radiarta et al. 2008). As this is a tool for regional scale planning, it was important to not limit the model to any one particular species. The decision of species type is best addressed in the aforementioned site selection model that must be created and implemented using the outputs of this model.

The primary sources of publicly available data were the Hawai‘i Aquaculture Development Program, the Hawai‘i State GIS Repository, and NOAA. Datasets from publically available sources often cover multiple areas. Selection of data to within the three-mile boundary around O‘ahu ensured that only pertinent data were analyzed. As there were multiple sources for bathymetry the one that contained the most coverage was chosen. This was not the most recent and detailed bathymetric survey from NOAA as it covered a less complete area around the island. The bathymetry data were incomplete and thus interpolation was conducted to fill the gaps in coverage. Nearest Neighbor interpolation was conducted as it uses the least amount of mathematical manipulation of the data, and utilizes the actual data surrounding the missing area to fill in the gap. The simplified formula for the Environmental subset is:

Enviro-Biological = Bathymetry

Using the adapted FAO formula (Aguilar-Manjarrez and Nath 1998), the bathymetry was analyzed at 3 different ranges. The first level (most suitable) allows for least financial input in anchoring materials hence 25m-50m. The next level (moderately suitable) is 51m-75m, and involves a greater cost in materials. The last level (76m-100m) is determined as least suitable due to the costs of materials as well as the need to employ specialized divers to maintain the equipment.

Economic

There are numerous financial considerations involved in an aquaculture operation such as cost of feed, labor, and material costs. These are all costs which do not translate well into a geospatial framework. However, there are several costs which can be well addressed spatially such as distance to markets, distance to shore-based support centers and distance to harbors (Radiarta et al. 2008).

As part of formulating the model, due care was taken to analyze each of these to determine which were the most valuable to include in a minimal dataset, as well as which were best addressed in a geospatial framework. Radiarta *et al.* (2008) included three factors all addressing distance: to town (a proxy for labor), to piers and to land facilities (a proxy for support). Within a minimal dataset, all three of these can be consolidated to distance to harbors. The equation for Economic subset becomes:

Economics = ([distance from harbors])

As with the environmental section, the economic data were defined on three parameters. There are two types of common support vessel, those that travel at 9 knots/hour, and the more expensive larger 15 knot/hour model (Sims 2008). The 9 knot/hour model was chosen to allow the greatest amount of buyin by potential users. The assumption was made that most operators will not want to pay the cost of having idle support teams traveling long distances; hence a 1 hour travel limit was imposed with areas closer to harbors being preferred (Sims 2008). The categories were then quantified as: "most suitable," 1-3 nautical miles from the harbor; "moderately suitable," 4-6 nautical miles; and "least suitable," 7-9 nautical miles from the harbor.

Social

This section considers traditional uses of an area as well as State of Hawaiʻi designated recreational uses. Though there is considerable information on the uses identified (including sailing, and diving and surfing), not all data is appropriate or valuable. Each available layer was analyzed for appropriate scale and value of input that it provided for the completed model before inclusion. In the final assessment the most consistent data for current social uses was determined to be designated recreation zones. This layer was presented in well defined polygons and required little manipulation to format it for use in the model. Other useful data would have been specific recreational uses such as sailing, fishing, windsurfing, and scuba diving areas. However, this data were presented in point format which involved the need for the creation of a buffer. As no valid information was available on determining a standardized buffer for all the potential recreational activities, it was not included in this model.

The difficulty in this section arose with *ahupua'a* offshore areas. The *ahupua'a* is a traditional land division similar to the modern concept of a watershed. During the Hawaiian Kingdom era these divisions included not only terrestrial but also marine boundaries. No data layer existed identifying the offshore portion of *ahupua'a*. In order to address the issue of Hawaiian traditional uses of offshore areas, previously published maps had to be digitized and incorporated into the model. Traditional Hawaiian interests were gathered from existing published and internally composed literature from University of Hawai'i at Mānoa urban and regional planning sources. As these descriptions are limited, and maps have digitization errors of up to 1.5X the scale of the map (Helsley and Umemoto 2003), all efforts were made to minimize these errors by careful digitization and comparison with the original hand drawn source, the accuracy of which may also be in doubt.

The combination of current and traditional use data, in the absence of published community or government preferences led to the creation of multiple scenarios. In an ideal situation the community or government would have provided input to determine their preference scale and appropriate weights could have been assigned to these layers in a WLC model. However, the lack of such preferences allows for the simplified creation of scenarios based on Boolean operations. The simplified exampled of Boolean operations format for the Socio-Political subset which created the following sub-scenarios:

Socio-Political = Σ *(([traditional area]* AND ([current use]))*

Socio-Political = Σ *(([traditional area]) OR ([current use]))*

Though the particulars of the data generated in this area are specific to Hawai‘i (particularly O‘ahu), the general concepts remain transferable. Most coastal areas around the world have long-established coastal communities with fisheries. It is this aspect of identifying "restricted" or "traditional-use" areas that is at the heart of this subset.

Comprehensive

This portion is the aggregate of the previous portions of the framework, which combines the total output of the environmental, economic, and applies the outcome through the scenarios presented in the social frameworks section. Using the WLC format, the environmental and economic layers are weighed equally and an output was generated, which was then filtered through the social scenarios.

As both the environmental and economic have 3 degrees and both are weighed equally, the ArcGIS WLC program functions by taking the value of the raster cell and multiplying it by the determined weight. The WLC then adds the values of the cell from each of the layers together to determine the output value of the cell. The general equation for the WLC is:

Comprehensive= Σ *(([Enviro-Biological]* $* x_n$*) + ([Economic]* $* x_n$*))*

An example is a cell which has a value of 2 and a weight of 0.5 in one layer, and a value of 1 (weight 0.5) in the other layer: ((2*0.5) + (1*0.5)) =1.5. As the output of WLC must be discrete and not floating point, the values are rounded up or down. If the value is X.5 and above the value is rounded up to X+1, else the resulting cell value is rounded down to X.

Scenario Modeling / Sensitivity Analysis

One of the key features of GIS and MCDE is the ability to change the valuations of inputs to achieve different results with relative ease. The goal of this project was to create such a simplified framework that users would be able to input their own weighted values based on their assumptions and compare the results with those of other users. This enables increased transparency in decision making at government levels and helps foster discussion with interested stakeholders.

Three general scenarios were created for original comparison:

- General: This scenario includes the entire three mile limit area around O'ahu without any constraints or limitations.
- Basic: This consists of publically released data of areas that were determined to be incompatible with the exclusive use requirements of offshore aquaculture.
- Military: This scenario contains the basic constraints as well as data on the military zones held in State of Hawai'i databases but not released to the public.

As mentioned previously within the Social subset, it was determined that though the concept of a social input in the comprehensive model is valid, no data from published sources or from discussions with the State of Hawai'i personnel mentioned the alteration of currently existing recreation zones or the official designation of *konohiki* fishing areas. This subset of scenarios was an all or nothing affair in that: all *konohiki* sites are available or no *konohiki* sites are available; all ocean recreation zones are available or no ocean recreation zones are available; all ocean recreation zones but no *konohiki* sites are available and no ocean recreation zones and all *konohiki* sites are available for aquaculture development. The resulting differences in available area were then compared to identify the impact of the socially important areas on potential aquaculture development sites.

Sensitivity analysis on the model was conducted via a system of alternate weights applied to the most restrictive Military scenario. In the absence of published information, it was chosen to highlight each of the primary entries into the WLC model. First a weight of 0.75 was chosen for Bathymetry, while the corresponding Distance from harbors was weighted at 0.25. The next iteration of the model switched those values, i.e. Bathymetry was weighted at 0.25, while Distance from Harbors was weighted 0.75. This provided an insight into how the model was producing the results, and indicated to which particular variable it may be sensitive.

Framework Verification

The output generated by this framework (appropriate areas for offshore aquaculture in the waters off O'ahu) was compared to existing offshore facilities (Cates International). Comparison to the previously existing Phase 1 model generated by the Hawai'i ADP was not appropriate as the models contained different set of data and utilized different premises to generate their output. The technique of verifying a framework by comparing it's output to pre-existing facilities is an established FAO practice which minimizes costs (Aguilar-Manjarrez and Nath 1998).

Chapter 6 Results

Given the complex nature of Hawaiian environmental regulations, and the contentious nature of development in Hawai'i, the number of sites available for offshore development around O'ahu is limited.

There are many sites that met the Environmental limitations, and even the Economic limitations. However, with the addition of Socio-Political factors, suitable sites are much more limited. Rather the limited number of sites available is indicative of the complex social and regulatory systems which are present in Hawai'i. Application of the framework in locations other than Hawai'i, which may be more open to aquaculture, would allow identification of more areas appropriate for aquaculture development. In all cases, it is anticipated that this regional analysis conducted by planners would be followed by a finer-scale assessment. This will limit the resources spent in detailed studies of wide regions; rather, the detailed, expensive site analyses can be focused on areas identified with this simple cost-effective framework.

Format

The limits of the model were the 3 mile state exclusive zone around the island of O'ahu, Hawai'i. As some data were provided as point data, it had to be converted to polygon data for initial use with the buffers. These polygons were then transformed into rasters with a $100m^2$ cell size. This was determined to be a reasonable size that provided a compromise between the coarseness of available data, as well as the desired fine resolution of a decision model. The viable size of an offshore cage operation (based on the currently operating facility in O'ahu) is over

3ha, hence a cell size of 1ha would allow this model to be introduced into areas where smaller operations may be initiated.

Induced Error

As most models run in a GIS space are raster based, all polygon layers were converted to raster format. This however introduces a 'pixelating' effect on the data and hence an error. Based on the comparison of total area determined by the polygon area of the 3-mile limit around O'ahu (1,310,550,814 m^2) and its raster equivalent (1,310,550,784m^2), there was a loss of only 30m^2 in the transformation (Table 3). This is unavoidable when using raster data due to its 'pixelated nature' (Figure8) and is considered to be an insignificant error that has no effect on the selection of suitable sites for aquaculture development.

Table 3 Difference in Area around Oahu between Polygon and Raster files

Layer	Area (m^2)
O'ahu Polygon	1,310,550,814
O'ahu Raster	1,310,550,784
Difference	30

As mentioned previously, the bathymetry data were incomplete. To alleviate this and provide full coverage, the Natural Neighbor interpolation tool in ArcGIS was used to fill in gaps. This is but one of several interpolation tools available. Natural Neighbor was chosen as it uses preexisting numbers in the algorithm and not a deduced number. It has been found accurate and is currently being used by NASA in their Mars Global Survey program (Abramov and McEwen 2004).

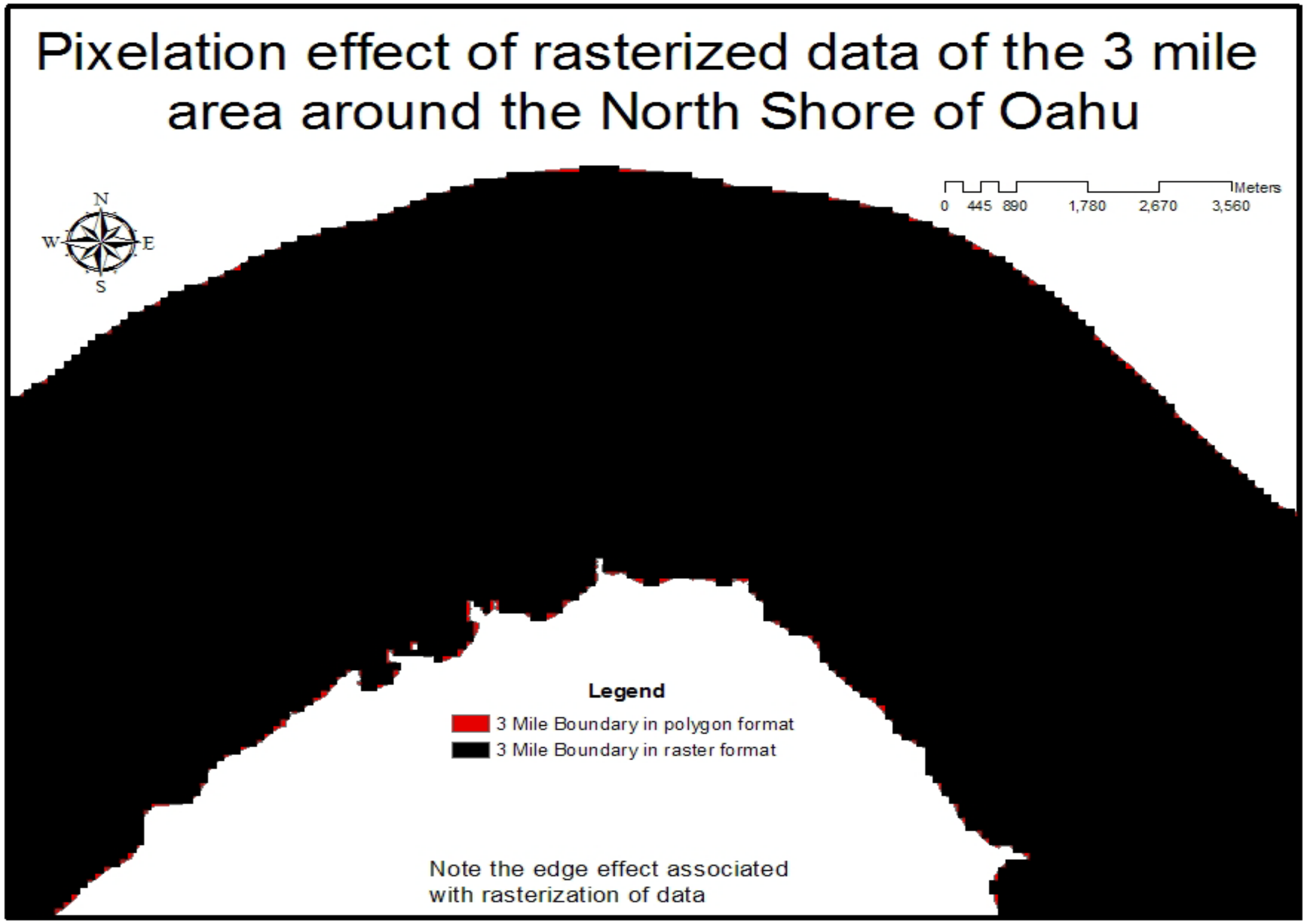

Figure 8 Pixelation of data evident when converting between Polygon and Raster data types

Basic and Military

The determination of areas to include in the basic layer has to be as complete as possible. Data that have to be included in this Basic area are identified as having some form of contradiction with the exclusive use property of offshore aquaculture. Not only do these layers have to be identified and added to the basic layer, appropriate buffers should be applied to them as well. Though there were few layers that did not have a buffer applied, most layers had a minimum buffer zone of 30m. The 30 meters was determined as the distance from the cage at which bacterial levels reach ambient proportions (Cates International Inc. 2000).

Layers which were included in the primary publically released basic layer include: anchor points (100m buffer to account for vessel movement), submarine buoys (100m buffer), cables (350m buffer determined by the size of cable repair ships and the tethered repair ROVs), corals from the navigational charts, as this was the most complete coral data provided by the State (30m buffer to account for bacterial levels). Dumping areas had no buffer, and explosive dumping areas though not contained within the 3-mile limited off Oʻahu were added for completeness and had no buffer. Fish aggregating devices, are devices used by the public for recreational use, and were given a 100m buffer to prevent conflicts. Fish havens and fish management areas have no buffer associated with them as it was assumed that a buffer was already applied when these areas were designated. Marine life conservation districts, and marine managed area both have 30m buffer zones, as do underwater obstructions. Navigational aids, which are similar to buoys, have 100m buffers to prevent anchor lines and service ship interaction. A 100m buffer was applied to underwater obstructions as these structures provide a hazard to navigation that is also incompatible with aquaculture. Offshore installations have prior uses and thus have a 100m buffer. Sewer lines have a 100m buffer to accommodate occasional unexpected sewage spills from affecting the farm. Unexploded Ordinance, included for completeness, were a point data file, and thus not very helpful, however a 100m buffer was used to approximate the spots, none of which occurred within the 3 mile area around Oʻahu. Wrecks were point formatted and included planes and vessels of various sizes; an average buffer of 100m was used to accommodate type variance. Table 4 provides the complete list of layers and their buffers.

As part of the scenario modeling process, military restricted sites are included in the basic layer as one of the two large scenario groupings. These military areas are zones in which the military has precedence of use and hence the exclusive use requirements of offshore aquaculture are incompatible. Though the military site data is acknowledged by the State it is not released publically across their servers and special permission must be sought to use it. Consequently there are 3 general scenarios, one which is based solely on the three-mile State boundary without any constraints, one with Basic constraints and one with Military constraints. Figures 9 and 10 identify the Basic and Military constraints individually; Figure 11 denotes the differences between Basic and Military constraint layers (those areas lost from the Basic scenario due to military constraints), while Table 5 represents the area available in total in all three general scenarios.

Table 4 Layers and applied buffers contained in Basic and Military scenario

Layer	Buffer (m)	Notation on Buffer
Anchor	100	Assuming various vessel sizes and drift
Cables	350	Based on repair ship limitations
Coral (NOAA Navigation Charts)	30	From Cates EIS, 30m is distance from cage where bacterial levels reach ambient concentrations
Dumping	None	Buffer assumed during designation
Explosive Dumping	None	No areas within 3mile limit of O'ahu, added for completeness
Fish Aggregating Device	100	Analogous to buoys, State statutes prevent encroachment on Buoys
Fish Haven	None	Buffer assumed during designation
Natural Area Reserve	None	Only on Maui, added for completeness
Fish Management Area	None	Buffer assumed during designation
Marine Life Conservation District	30	From Cates EIS, 30m is distance from cage where bacterial levels reach ambient concentrations
Marine Managed Area	None	Buffer assumed during designation
Navigational Aide	100	Analogous to buoys, State statutes prevent encroachment on Buoys
Obstruction	30	Point file, buffer added for safety of operators
Offshore Installation	100	Based on point data, prevent overlap of exclusive use zones
Sub-surface Buoys	100	Analogous to buoys, State statutes prevent encroachment on Buoys
Sewer lines	100	Additional safety margin to prevent contamination during a sewage spill
Unexploded Ordinance	100	Point File and none within O'ahu 3 mile area
Wrecks	100	Averaged size of various wrecks (planes and ships)
Military	None	*Contains Multiple layers which author does not have permission to disclose

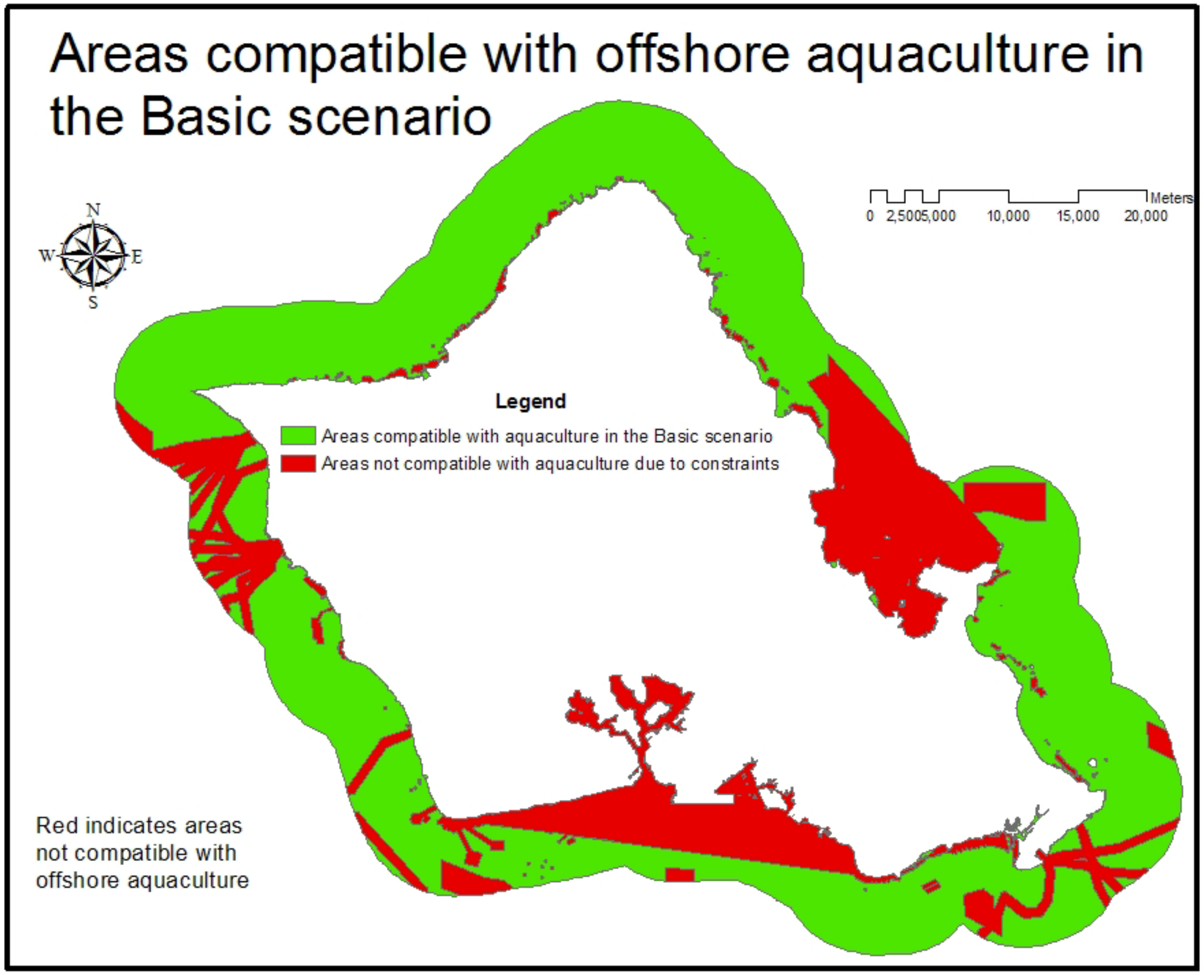

Figure 9 Basic constraint layer indicating areas of possible offshore aquaculture development determined by publically released data

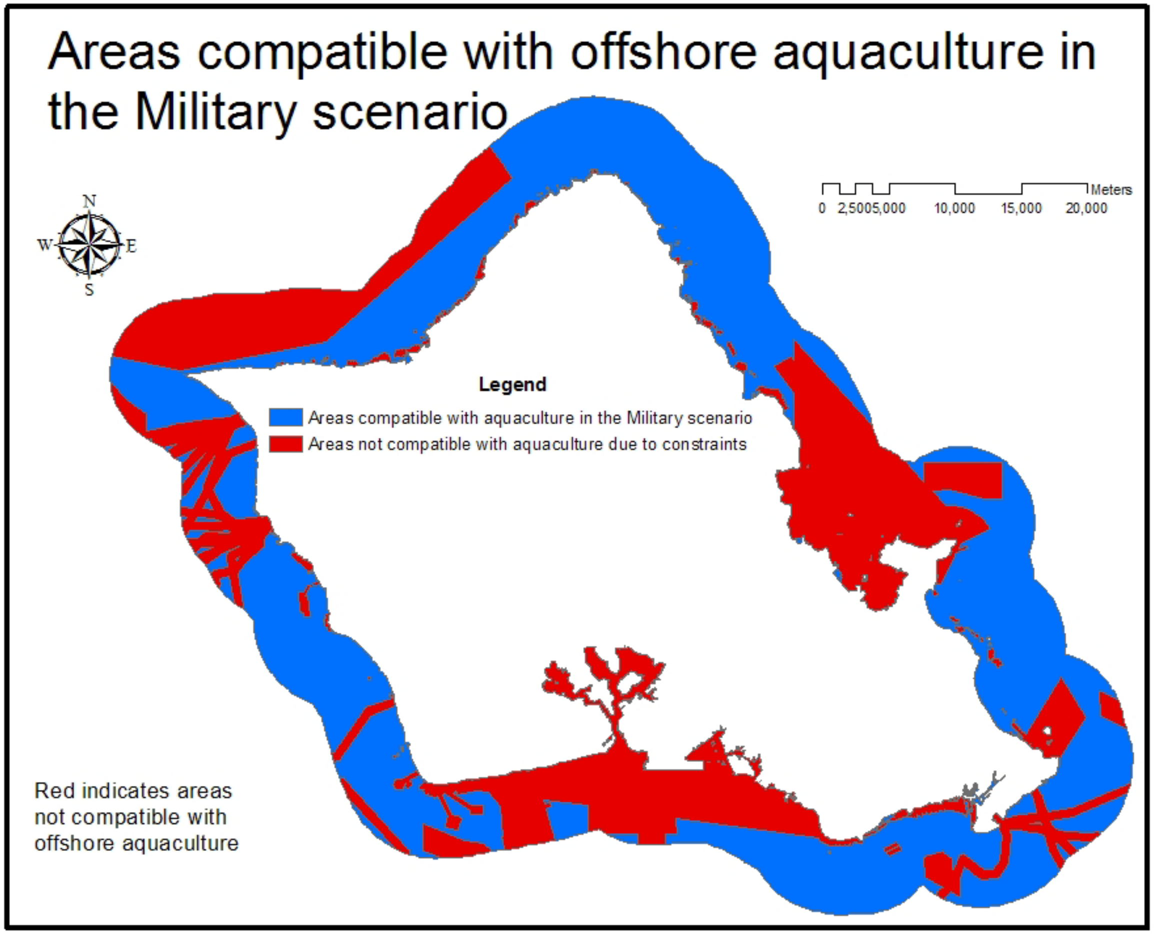

Figure 10 Military constraint layer indicating areas of possible offshore aquaculture development determined by State of Hawai'i held data

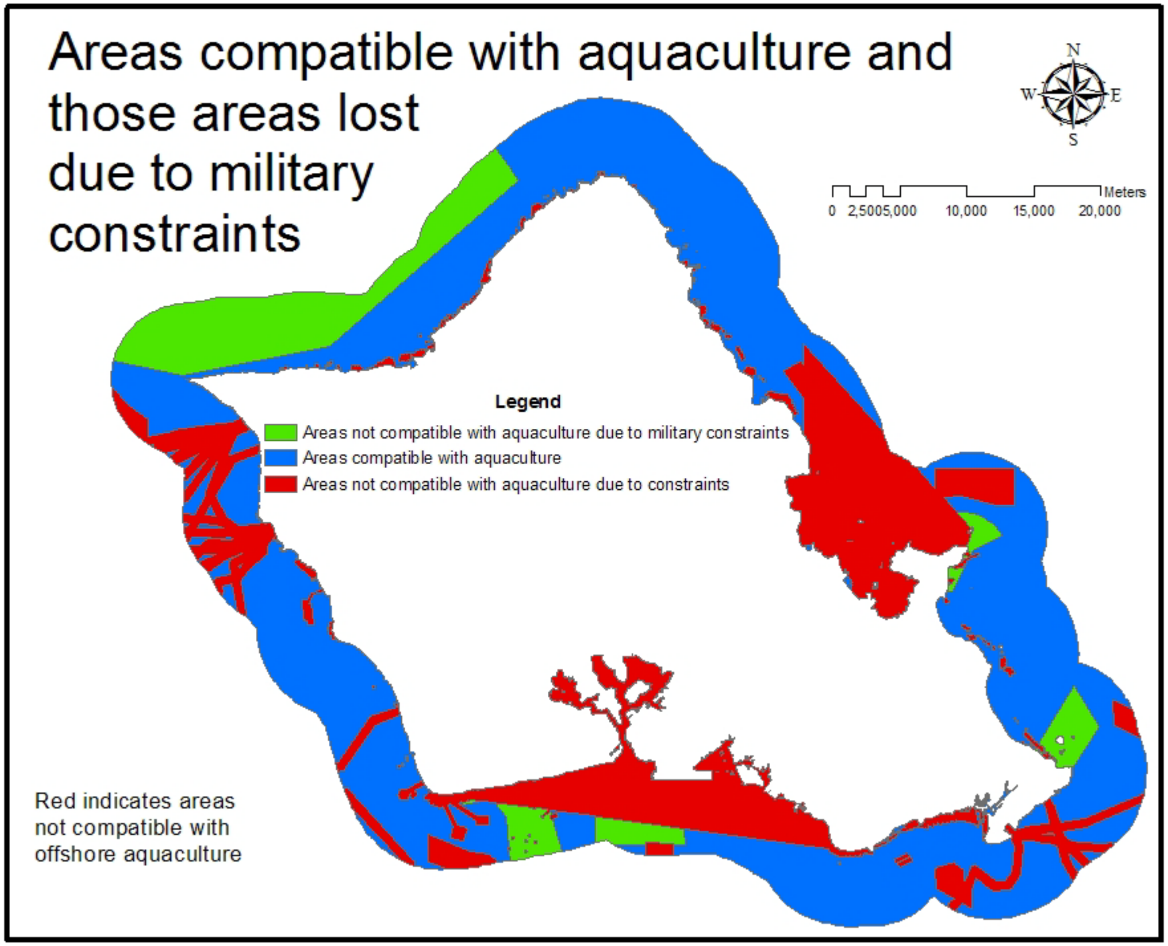

Figure 11 Comparison of Basic and Military constraint layers indicating areas of possible offshore aquaculture development determined by State of Hawai'i held data

Table 5 Size Comparison of 3 initial scenarios

Layer	Size (m^2)	%
O‘ahu Full Extent	1,310,550,784	100
Basic	924,000,191	70.5
Military	769,486,606	58.7

Environment

Technical information on the physical limitations of the culture cages was gathered from available public sources such as the Environmental Assessments of the Cates International and Kona-Blue operations, as well as the manufacturer's websites.

Though bottom-type is potentially valuable information, the variations are not necessary in this minimum dataset basic model. The only type of bottom habitat that is restrictive are those areas which are covered by coral, and these have been identified and excluded in the basic layer. The cage technology can potentially be situated on any other form of benthic habitat.

Previous models included several other environmental factors(Levings et al. 1995, Kryvi et al. 1991, Berris 1997):

- Currents; though useful in a detailed examination, these are difficult and expensive to collect and not appropriate for a minimal dataset model, as long as sites which are protected such as bays are excluded; currents can be included in subsequent detailed analyses;
- temperature; more appropriate consideration in temperate zones; by focusing the model on tropical areas and for species which are endemic, temperature becomes less important, and can be included in subsequent site selections;
- dissolved oxygen; locating the structures in areas with enough flushing (i.e. not in a bay) can ensure sufficient levels of dissolved oxygen;

- salinity; as these are offshore cages, freshwater input will be minimized, and hence salinity can be considered consistent;
- tides; technology of submerged cages allows for cages to be submerged 10m below the surface and thus not impacted by tides,
- turbidity; by locating the cages far from shore, sediment carried by runoff can be avoided;
- freshwater input; unless a location has an underwater freshwater seep, offshore cages are located sufficiently far from the mouths of freshwater discharges that it can be negated;
- flushing; analogous to currents.

Through the use of minimal dataset restrictions, it was determined that for a first pass model, the most important factor in the environmental section is depth. Depth is the determining limitation on both a species as well as a current technology. As sustainable farm operators will choose a local species to culture, the concerns over DO, currents, tides and salinity will be less of a concern. Additionally flushing is analogous to currents and hence can be disregarded for a first pass model. As this model is focused mainly on Pacific island uses, the temperatures do not vary dramatically between the seasons and most native species have adapted to handle the fluctuations. As this model focused on offshore cages located farther from shore, turbidity is of lesser concern. If however, a nearshore operation with different parameters were to be established the model could be adapted to incorporate this by identifying areas of terrestrial runoff (analogous to agricultural fields) and put those with an appropriate buffer in the basic section of the model. Tides are of less concern due to the technology used in offshore operations. These cages are suspended 10m below the surface and thus not as prone to impact as a cage tethered directly at the surface.

A mentioned previous, the most important environmental factor, from all aspects is depth. Cage technology is robust enough as to be tethered to nearly any depth if funds are not limiting. However, the deeper the tether lines the costlier it is in terms of materials as well as specially trained personal to service them. This model recognizes 3 viable depth zones:

- 25m-50m: The optimal zone for aquaculture as the cost of materials is acceptable, as well as being in the depth range of non-specially trained divers for service. These were weighted the highest value in the model.
- 51m-75m: Moderately desirable for aquaculture, the cost of materials has increased (longer tether lines) and specially trained divers are now needed to service the structures. These were weighted as second.
- 76m-100m: Least desirable but still viable if the operator has substantial funding. Material costs of tethering and anchoring increase as well as diver costs. These depths were weighted as third in the model.

Anything outside of these zones is either too shallow to qualify for offshore aquaculture or so deep that costs become prohibitive. Figure 12 indicates the 3 depth zones around the island of O‘ahu, while Figures 13 and 14 denote the differences between the Basic and Military scenarios. Table 6 also shows the total areas of each depth band in total as well as with the Basic scenario and the Military scenario.

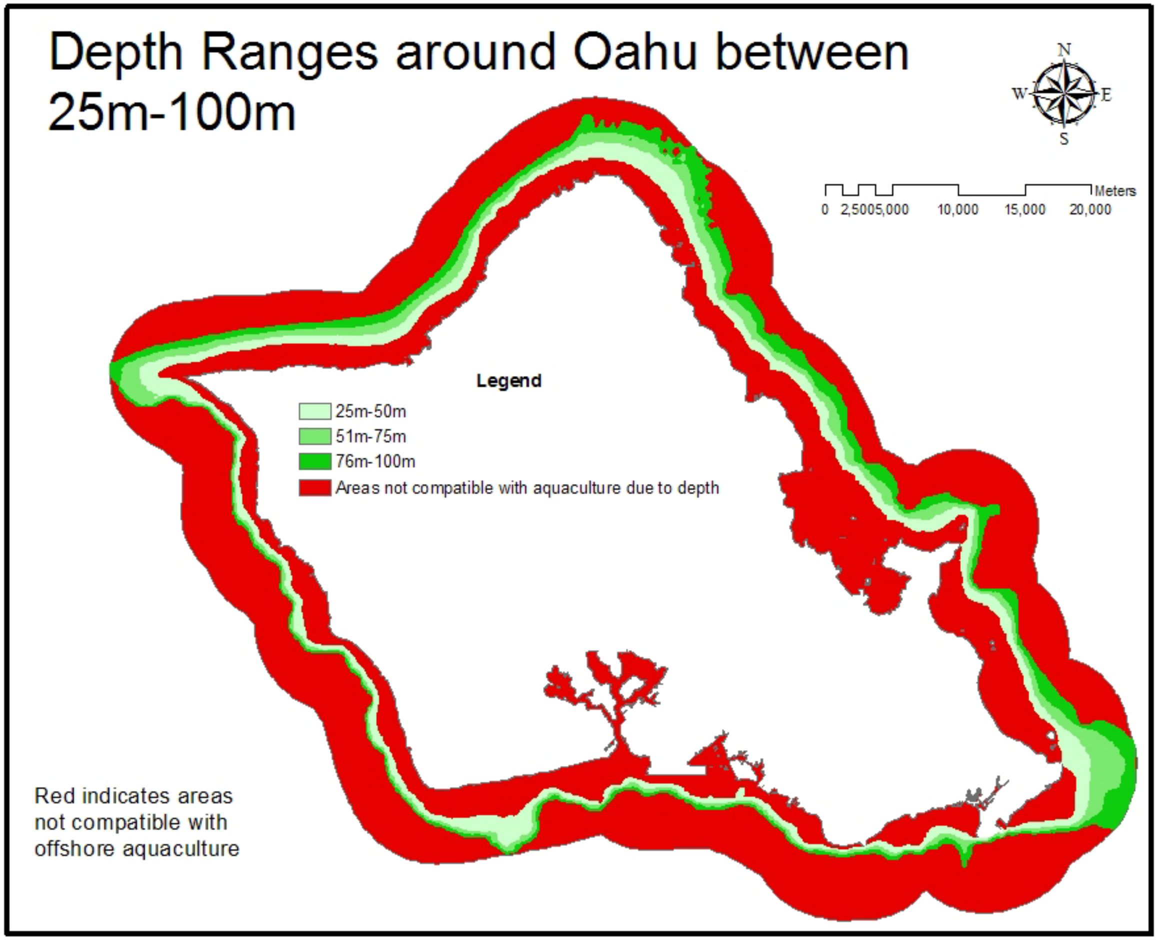

Figure 12 Depth Ranges between 25m and 100m around O'ahu

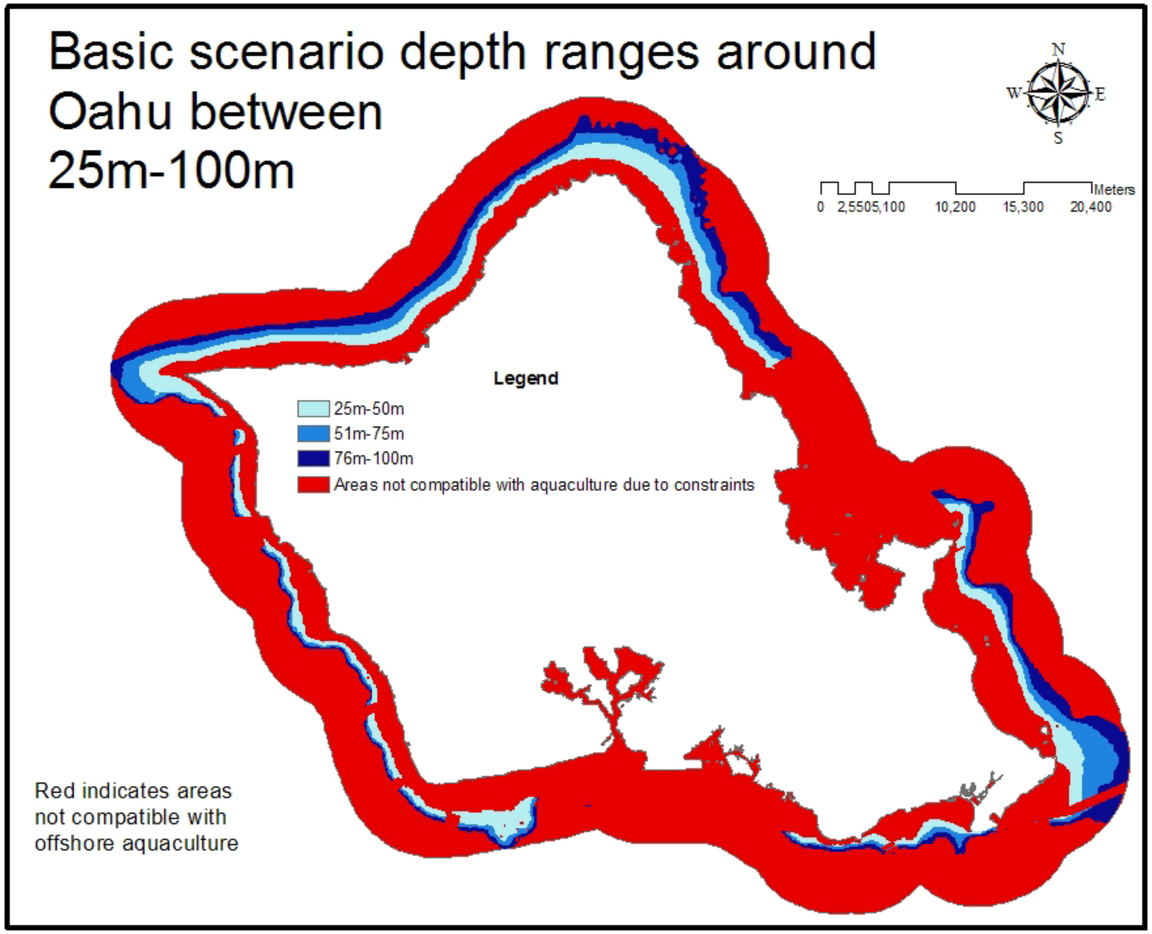

Figure 13 Basic scenario depth ranges between 25m and 100m around O'ahu

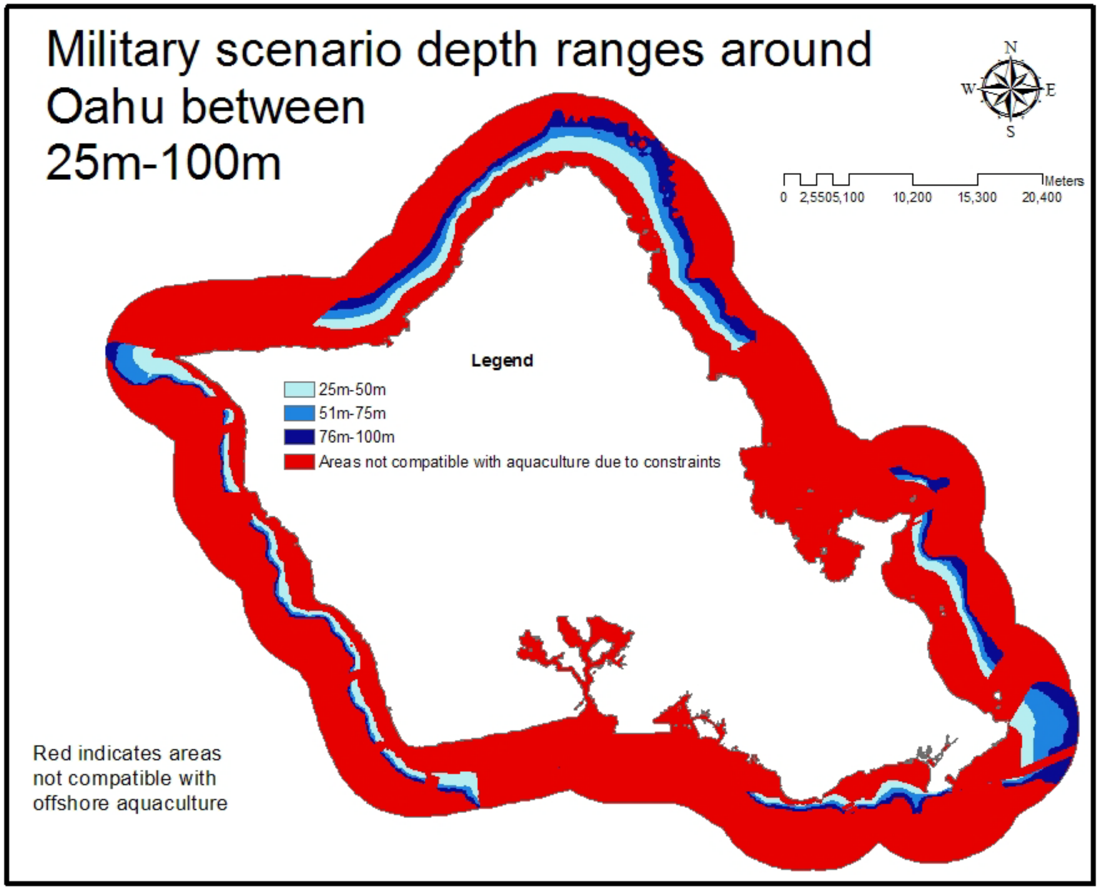

Figure 14 Military scenario depth ranges between 25m and 100m around O'ahu

Table 6 Depth ranges between 25m and 100m around Oahu in Total, Basic, and Military scenarios

Depth	**Full Extent Size (ha)**	**Basic Size (ha)**	**Military Size (ha)**
25m-50m	12,077	9,895	8,151
51m-75m	9,313	7,692	6,431
76m-100m	10,634	8,253	6,900
Total	32,024	25,840	21,482

Economics

Numerous aspects can be included in the economic decision sub-model. However, many areas where this model may be applied may not have the following layers available:

- Infrastructure; roads, though important to understand for access to onshore support facilities, by projecting that some facilities are located at harbor locations, this layer is not needed,
- Distance to markets; difficult to estimate and not appropriate for geographic minimal dataset geographic modeling,

Numerous other costs are associated with aquaculture (Martinez-Cordero *et al.* 2001). These include fixed costs such as feed, wages, materials (support vessels, onshore facilities, cages), and leases. None of these can be sufficiently addressed in a geospatial minimal dataset framework, and thus are not considered.

By focusing on minimal dataset requirements, and considering the transferability of this model, the information in this section contains:

- Distance from Harbors; which address the factor of cost of transport of personnel and materials to and from the site, from a shore support area. The farther the site is from the harbor the higher the cost, and thus the lower the return on investment.

Distance from harbors was a layer created by first identifying harbors, then buffering 3 rings around them (1-3knots, given the highest weight; 4-6knots, given the second weight; and 7-9 knots, given the least weight).

Figure 15 shows the 3 zones around the harbors. As they are rings extending from the harbor, the 9 nautical mile ring does not indicate 9 nautical miles from shore, but rather 9 nautical miles from a harbor; hence this does not directly address the visual blight question, whereby observers from shore might object to commercial activities at fixed points in the near coastal waters. As this is a minimal dataset model, this type of question is best addressed by predetermining points where visual blight would be a concern and excluding those in the basic layer, or address it in the more detailed second pass model that would have be used to complete the final site selection process. Figures 16 and 17 indicate viable economic distance from harbor areas within the Basic and Military scenario. Table 7 lists the available areas in the three scenarios.

Social

There are many aspects which can be included in the social dataset. These include recreation zones and previously established native cultural areas. One particular set of data that would be useful in this section was recreational uses. However the State of Hawai'i data itself is presented as point data. As point data contains no 'area' information (is one dimensional), it is less valuable in determining site suitability outcomes within a MCDM unless appropriate buffers can be applied (hence giving the data 2 dimensional attributes). The recreational use layer includes data on sailing sites and octopus fishing sites for example. Both of these activities are highly mobile and cannot be confined by a standard buffers. Attempts to do so would introduce large levels of error and would not enhance the model.

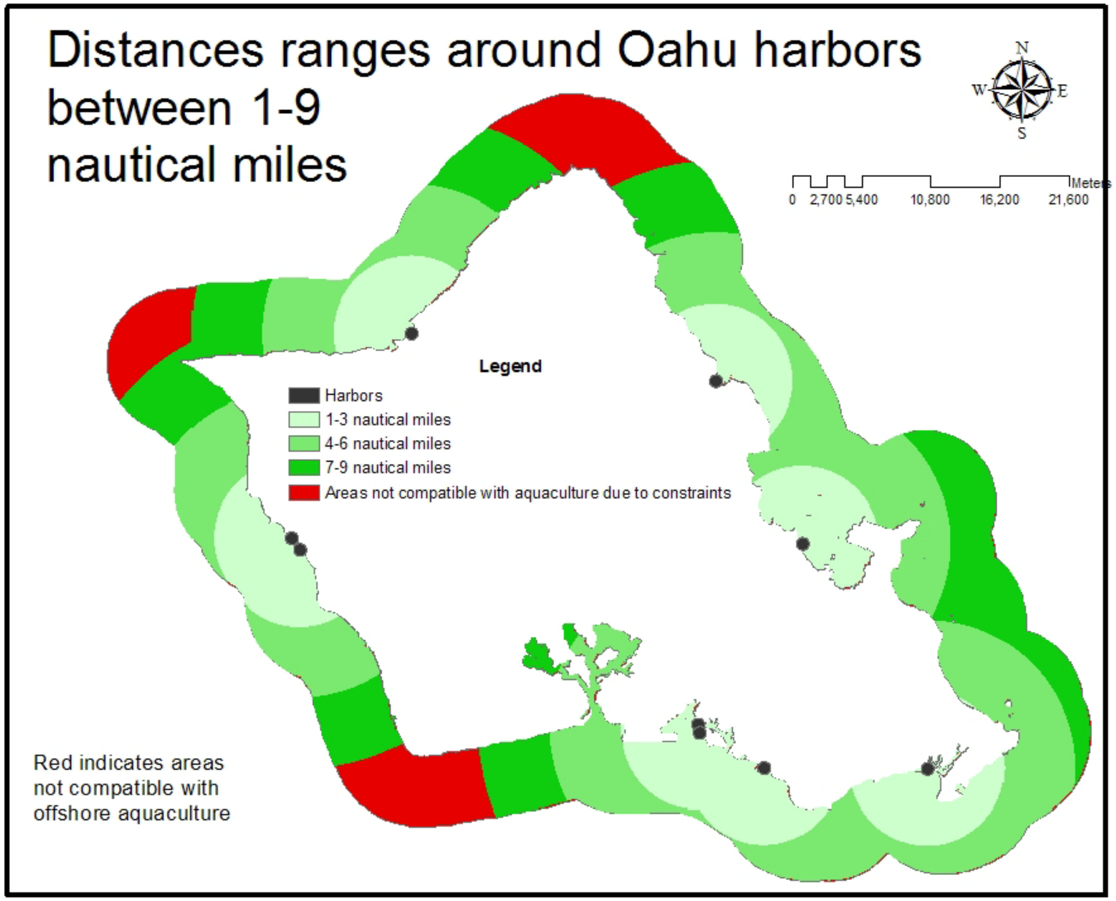

Figure 15 Distance ranges from 1-9 nautical miles around O'ahu harbors

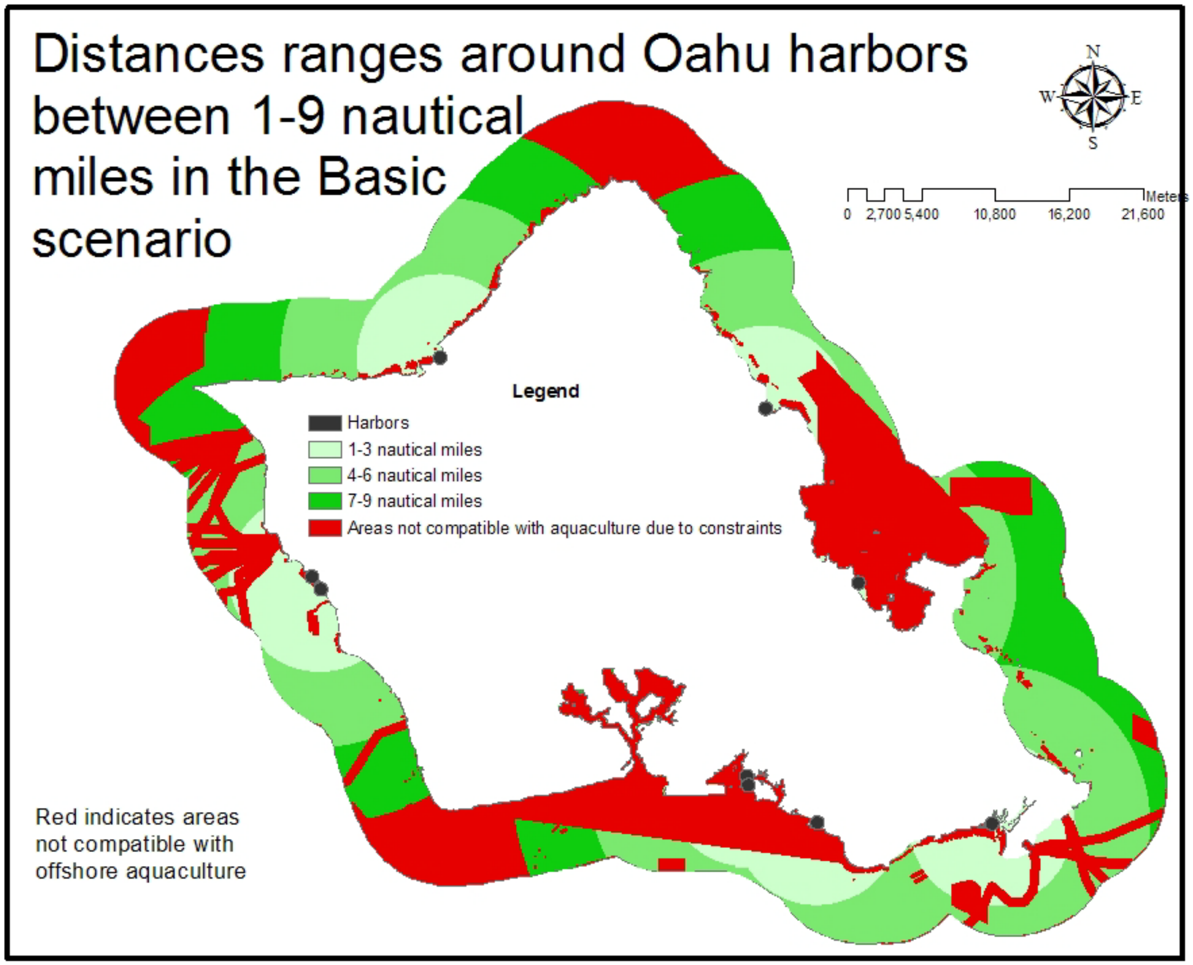

Figure 16 Distance ranges from 1-9 nautical miles around O'ahu harbors within the Basic scenario

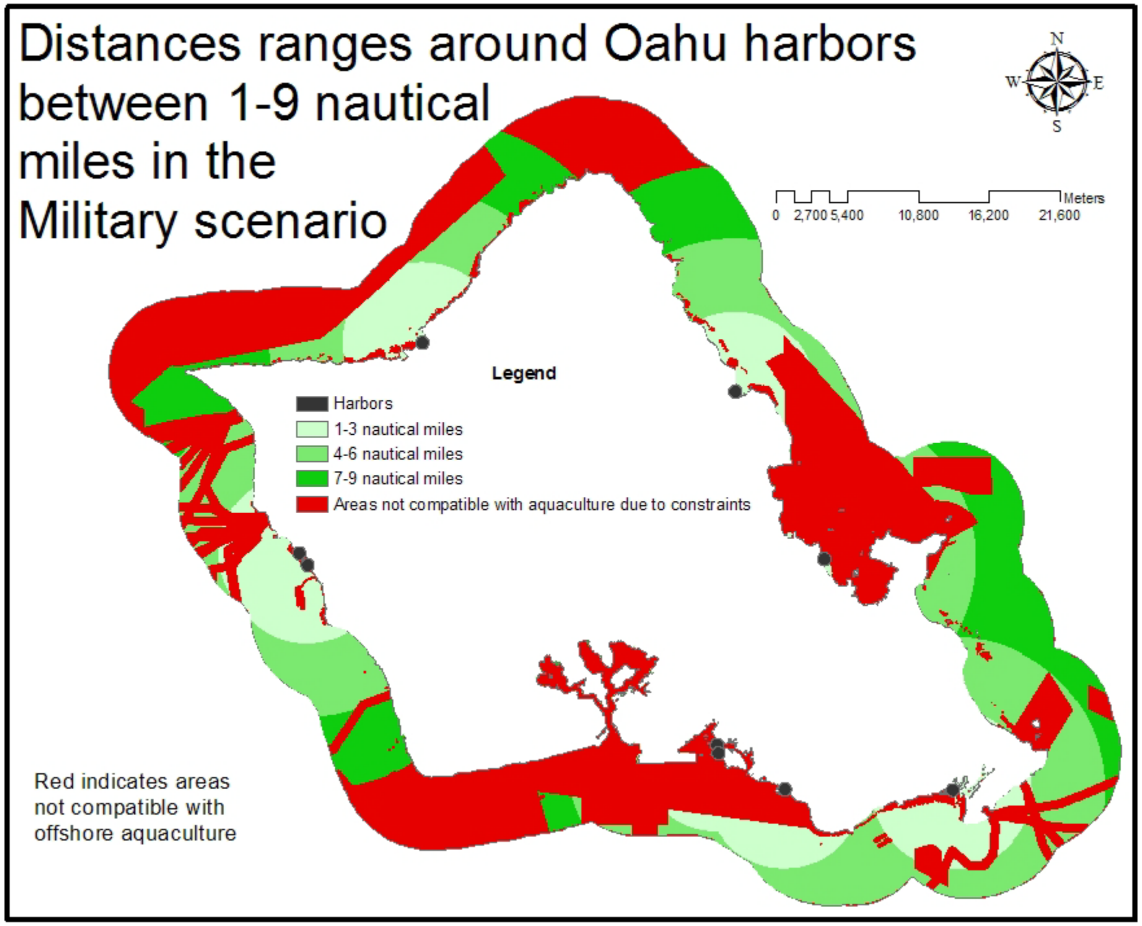

Figure 17 Distance ranges from 1-9 nautical miles around Oʻahu harbors within the Military scenario

Table 7 Distance ranges between 1 knot and 9 nautical miles around Oahu harbors in Total, Basic, and Military scenarios

Distance (nautical miles)	Full Extent Size (ha)	Basic Size (ha)	Military Size (ha)
1-3	33,008	17,361	16,995
4-6	51,878	36,186	29,078
7-9	30,441	25,490	20,284
Total	115,327	79,037	66,357

What the data does show though is that the entire marine area around Oʻahu is in use by some form of recreation. Consequently the political aspect of the model includes:

- Recreational Zoning areas: these zones are identified by the state as areas with prior existing uses, most of which will conflict with the exclusive nature of aquaculture leases. Even though recreation occurs outside of these zones the State of Hawaiʻi has designated the boundaries of these areas as specifically for ocean recreation;
- *Konohiki* Fishing Areas: these were described as being restricted from common use, and thus may be considered restricted by the native culture. These areas were described in late territorial literature (Kosaki 1954), were digitized by hand, and were previously introduced in chapter 1.

Figure 18 identifies the recreation zones in total. Figure19 represent the recreation zones present in the Basic and Military scenarios. Table 8 illustrates the area differences between the three prominent scenarios. There is no difference between the Basic and Military scenarios in total area.

There are 17,000 ha in *konohiki* fishing areas within the three-mile state boundary. Figure 20 represents these areas in total. Figures 21 and 22 represent the *konohiki* fishing areas open to competition with aquaculture in the Basic and Military scenarios respectively. Table 9 shows that several of the areas have been completely removed from inclusion in the model, leaving just over 9,000 ha in the Basic and Military scenarios.

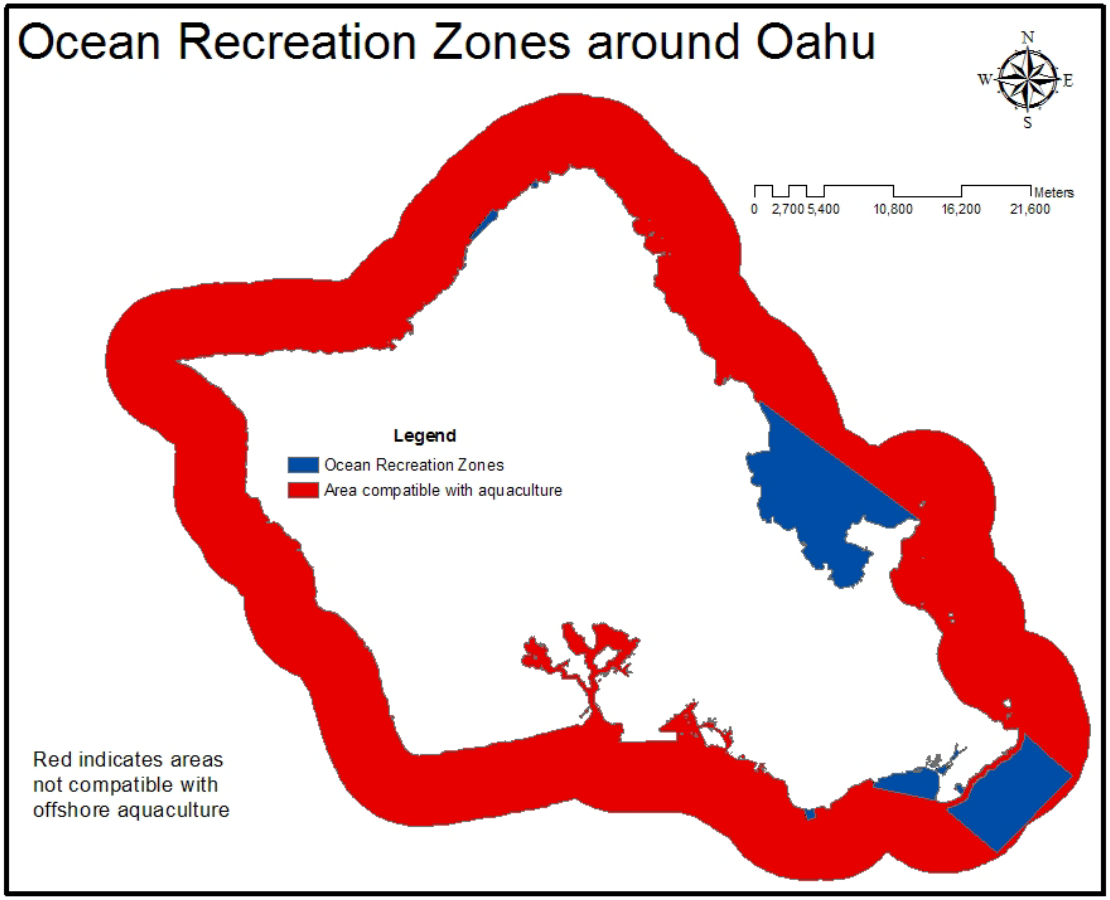

Figure 18 Ocean Recreation Zone around Oahu, areas may conflict with offshore aquaculture

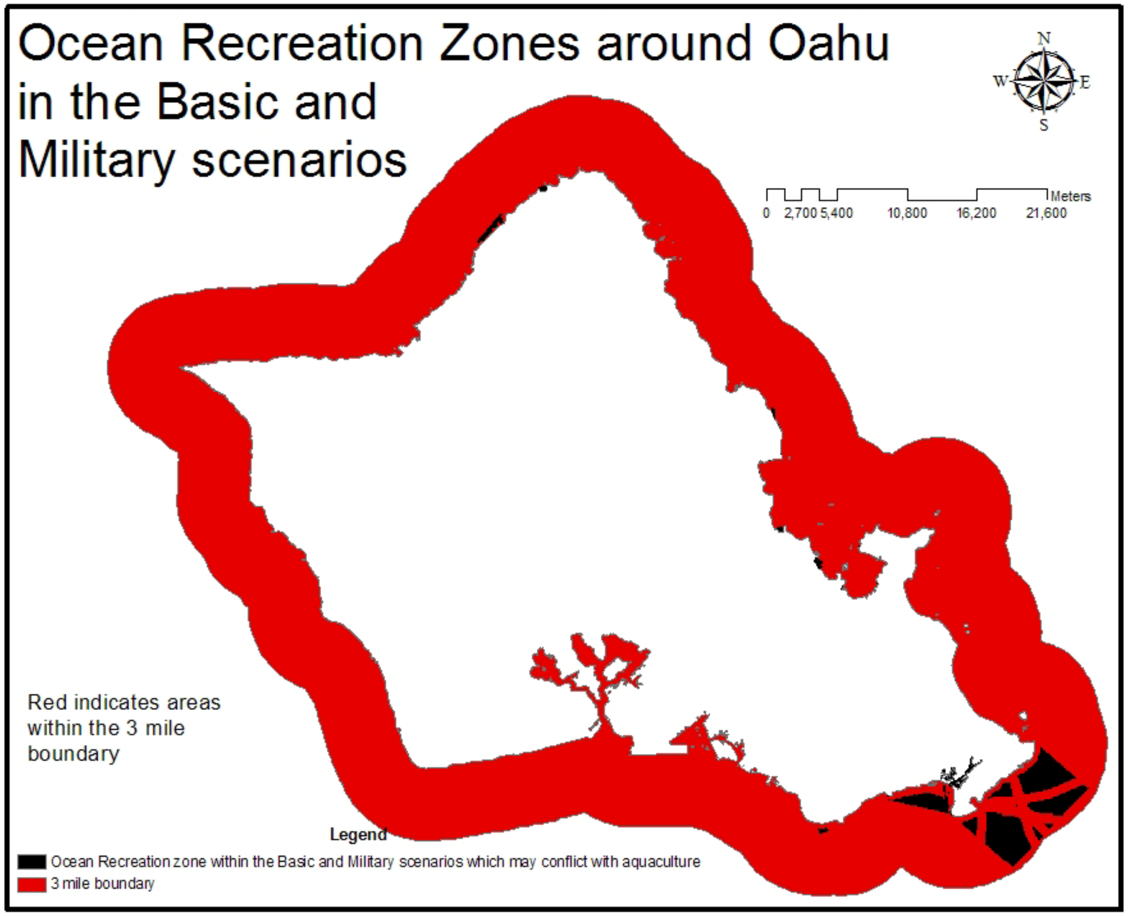

Figure 19 Ocean Recreation Zone around Oahu in the Basic and Military scenarios, areas may conflict with offshore aquaculture, note there is no difference between the Basic and Military scenarios regarding Ocean Recreation Zones

Table 8 Ocean Recreation Zone sizes (ha) in the Full Basic and Military scenarios

Ocean Recreation Zone	Full Extent Size (ha)	Basic Size (ha)	Military Size (ha)
Kawela Bay	18	18	18
Sunset Beach	128	109	109
3 Tables N	5	0	0
3 Tables S	6	0	0
Waimea Bay	10	0	0
Kāne'ohe Bay	7,997	76	76
Koko Head	4,018	2,606	2,606
Manalua Bay	950	527	527
Hanouma Bay	31	0	0
Diamond Head	53	22	22
Total	13,216	3,358	3,358

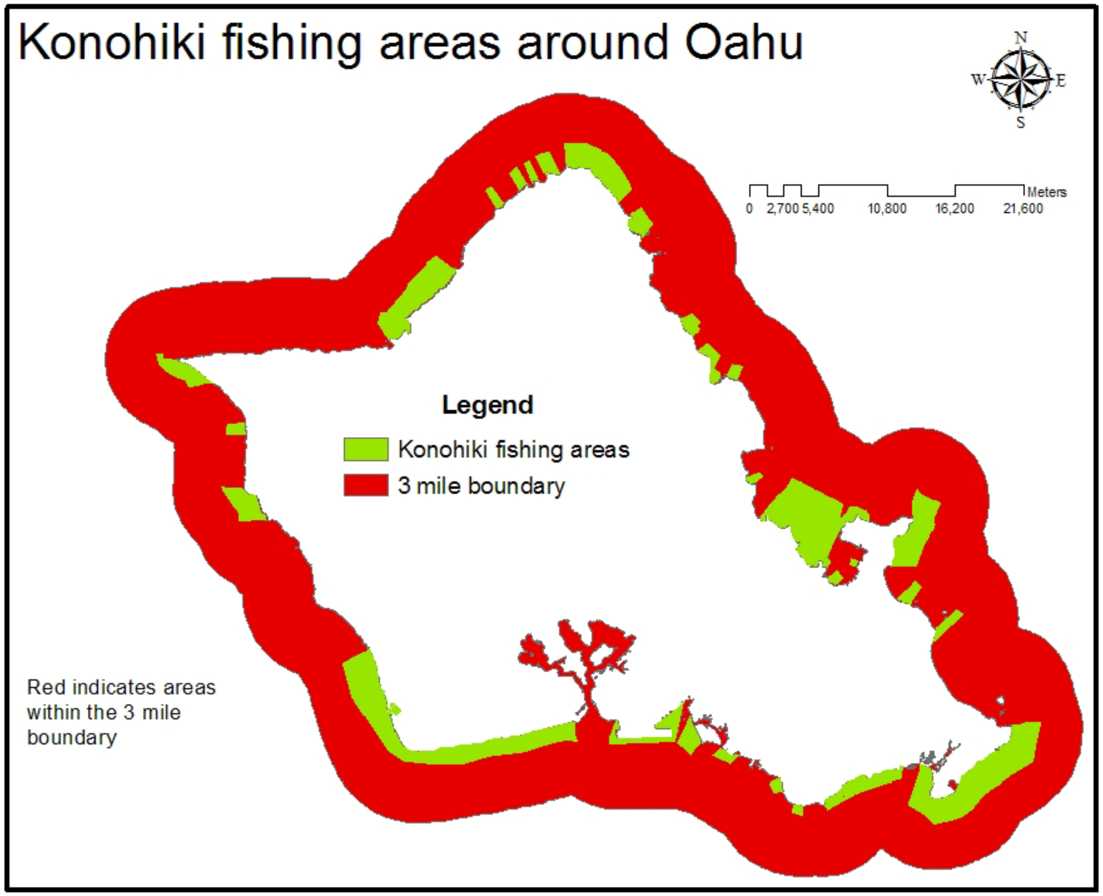

Figure 20 Konohiki Fishing areas around Oahu in the Total scenario, areas may conflict with offshore aquaculture

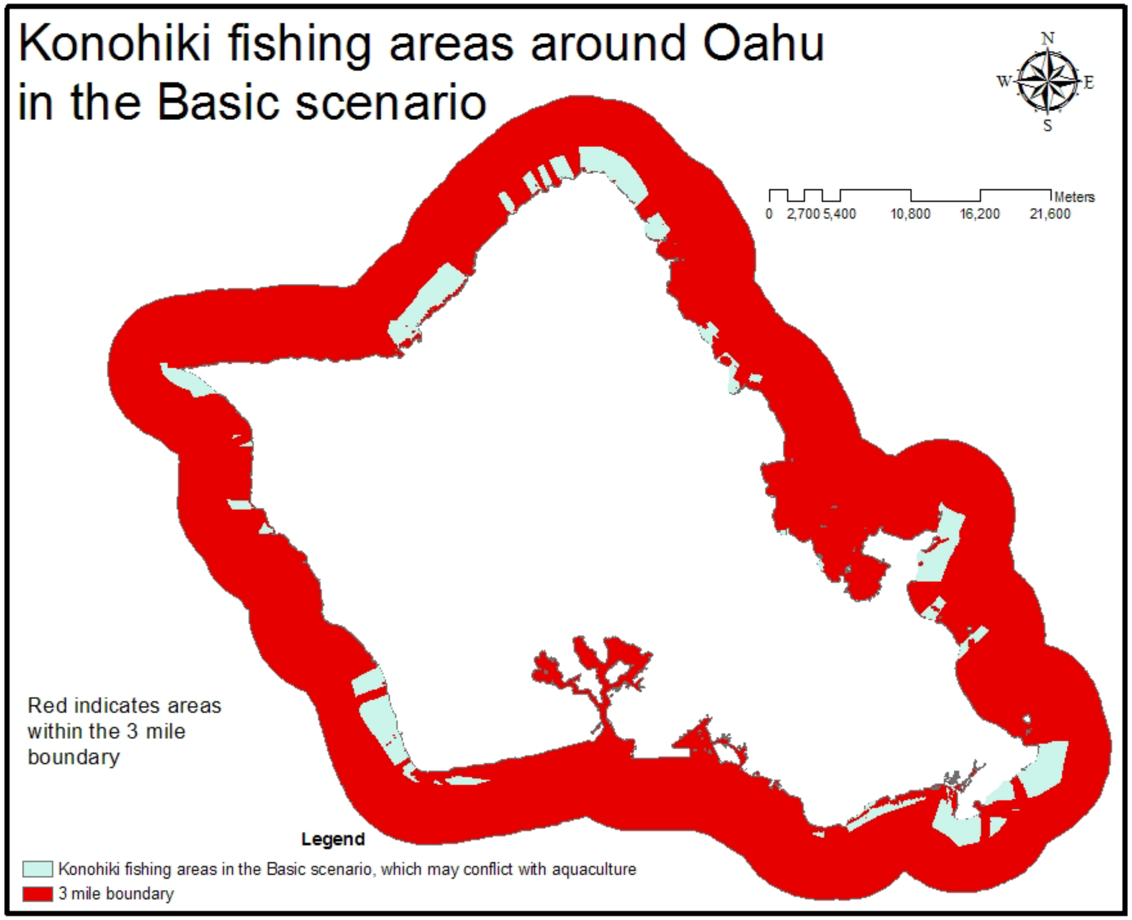

Figure 21 Konohiki Fishing areas around Oahu in the Basic scenario, areas may conflict with offshore aquaculture

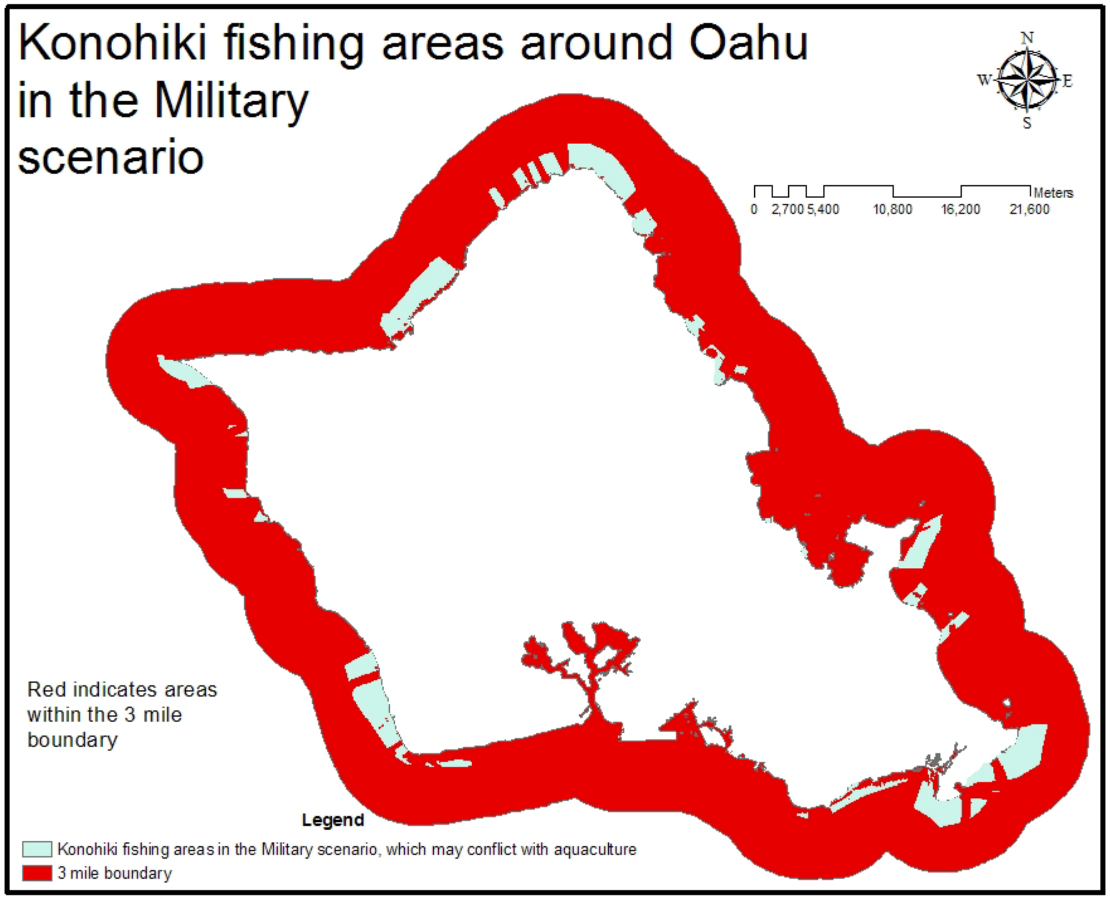

Figure 22 Konohiki Fishing areas around Oahu in the Military scenario, areas may conflict with offshore aquaculture

Table 9 Area of Konohiki Fishing Areas around Oahu in Total, Basic, and Military scenarios

Konohiki Fishing Area	Full Extent Size (ha)	Basic Size (ha)	Military Size (ha)
1	1,129	1,089	1,089
2	206	197	197
3	99	96	96
4	133	125	125
5	124	114	114
6	1,479	1,294	1,294
7	483	478	477
8	142	36	36
9	533	174	174
10	3545	1,564	1,529
11	548	5	5
12	271	0	0
13	31	0	0
14	117	0	0
15	87	0	0
16	67	29	29
17	149	109	109
18	227	148	148
19	15	72	72
20	112	34	34
21	17	0	0
22	2,962	2,189	2,186
23	204	172	172
24	157	137	137
25	1,152	1,022	594
26	32	0	0
27	86	1	1
28	36	0	0
29	184	0	0
30	1,197	30	30
31	1205	15	15
32	75	2	2
33	107	54	54
34	82	82	80
35	165	108	108
36	32	20	20
37	141	128	128
38	155	145	145
39	119	119	119
Total	17,605	9,788	9,319

•

Combined

Numerous results can be created by changing the weight options within a WLC equation. When using a minimal dataset with a lack of published information regarding the preferences surrounding the social aspects, the most appropriate way to address these limitations is through the creation of scenarios, which illustrate the effects of various combinations of the uncertain information

There have been no open discussions of either reintroducing the k*onohiki* fishing sites publically (though they still may be utilized by local families and hence can pose a barrier to implementation of offshore aquaculture); and no proposal by the State of Hawai'i to remove any particular Ocean Recreation Zone from designation. The following four scenarios cover the potential combination of outcomes.

- Combination of Ocean Recreation and Konohiki Fishing areas:
    - All Ocean recreation and k*onohiki* Fishing areas are available for exclusive use contracts associated with offshore aquaculture,
    - No Ocean Recreation or k*onohiki* fishing areas are available for exclusive lease, so these areas are considered not viable for offshore aquaculture (Figure 23),
    - Only Ocean recreation zones but no k*onohiki* fishing areas are available for exclusive use
    - Only k*onohiki* fishing areas but no Ocean Recreation Zones are available for exclusive use leases associated with offshore aquaculture.

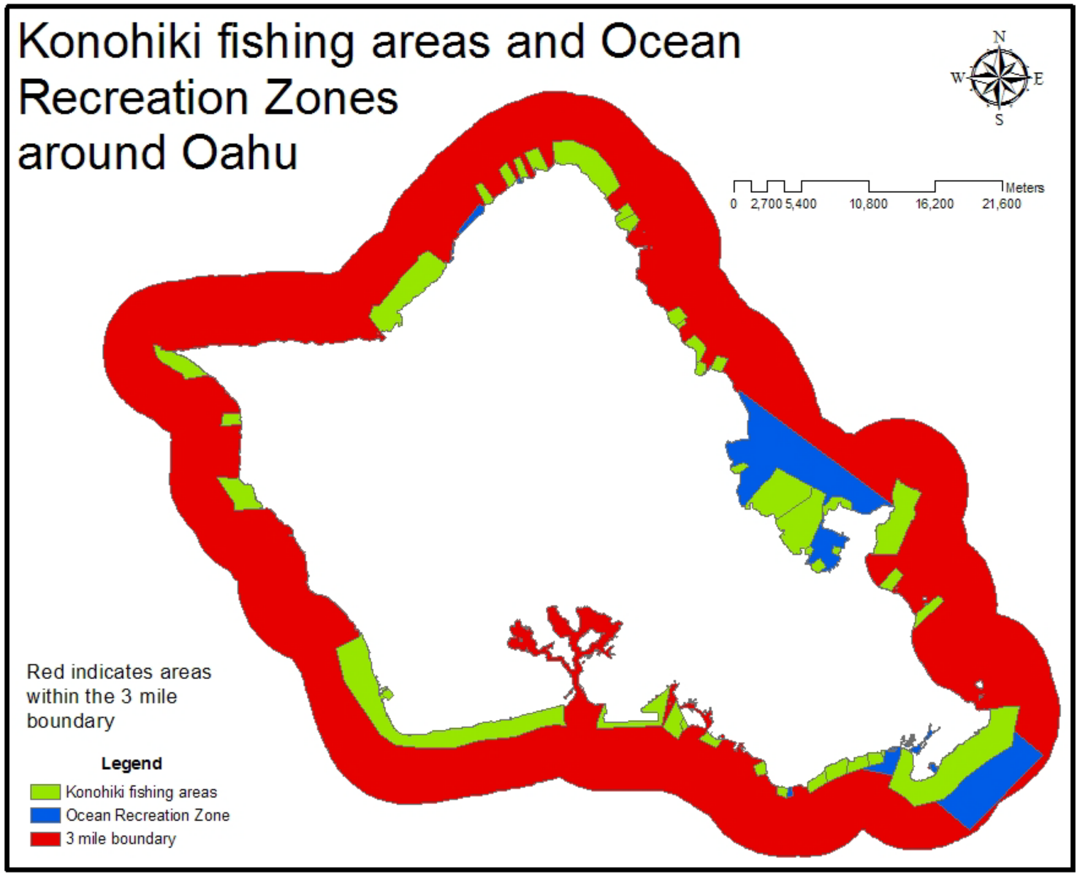

Figure 23 Overlap of Konohiki Fishing areas and Ocean Recreation Zones around O'ahu (note the overlap of area, which may be incompatible with aquaculture)

When running the WLC model on the environmental and economic data both at equal influence, it becomes clear that there are only a small portion of viable sites around O‘ahu available for offshore aquaculture. In the total three-mile area, 26,893 ha are available if no constraints are implemented (Figure 24). Of these, 3,304 ha are most suitable. In the basic and military constraint scenarios 20,210 ha and16,769 ha respectively become available (Figures 25 and 26 respectively). Within the Basic and Military layers only 2,020 ha of the overall 3 mile area around O‘ahu are classified as very suitable (Table 10).

When including the 3 social scenarios with the 3 general scenarios, differing areas are identified as compatible with offshore aquaculture. When neither the *konohiki* fishing areas nor the ocean recreation zones are limited then the values for all three basic scenarios remain constant as reported previously. However, when both the *konohiki* fishing areas and the ocean recreation zones are determined to be incompatible with exclusive use leases, then the totals are 17,195ha and 13,965 ha (Figure 27 and Table 11). For the case of All *konohiki* fishing area are off limits but ocean recreation zones are viable then the results are 17,779ha and14,549ha (Table 12). For the case of all Ocean recreation zones being off limits but no konohiki fishing sites are limiting then the results are 19,443ha for both the basic and military exclusion scenarios (Table 13). This degree of equivalence indicates that there is little difference between the basic and military exclusion scenarios with respect to their overlap of designated ocean recreation zones.

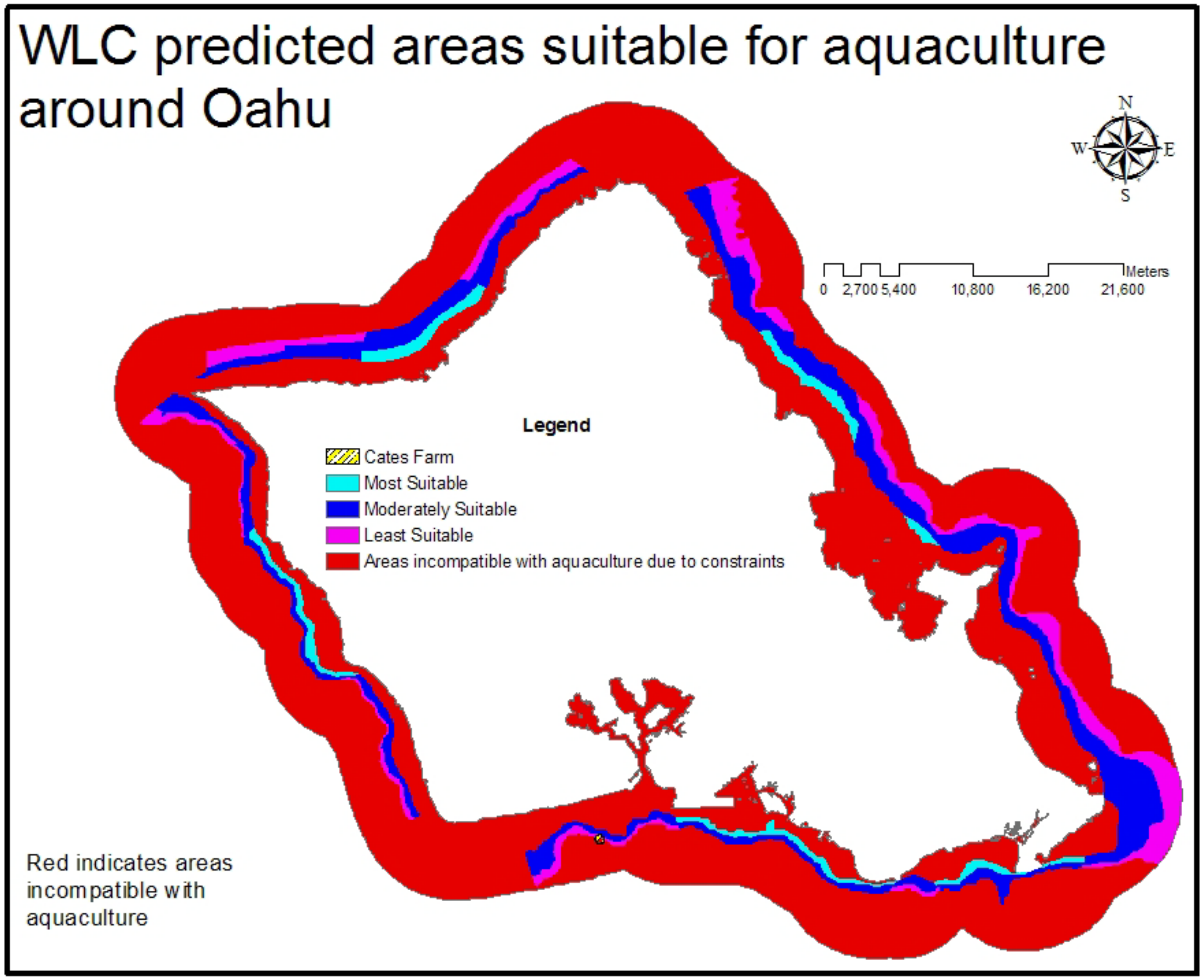

Figure 24 Predicted suitable areas for offshore aquaculture based on environmental and economic parameters at equal value

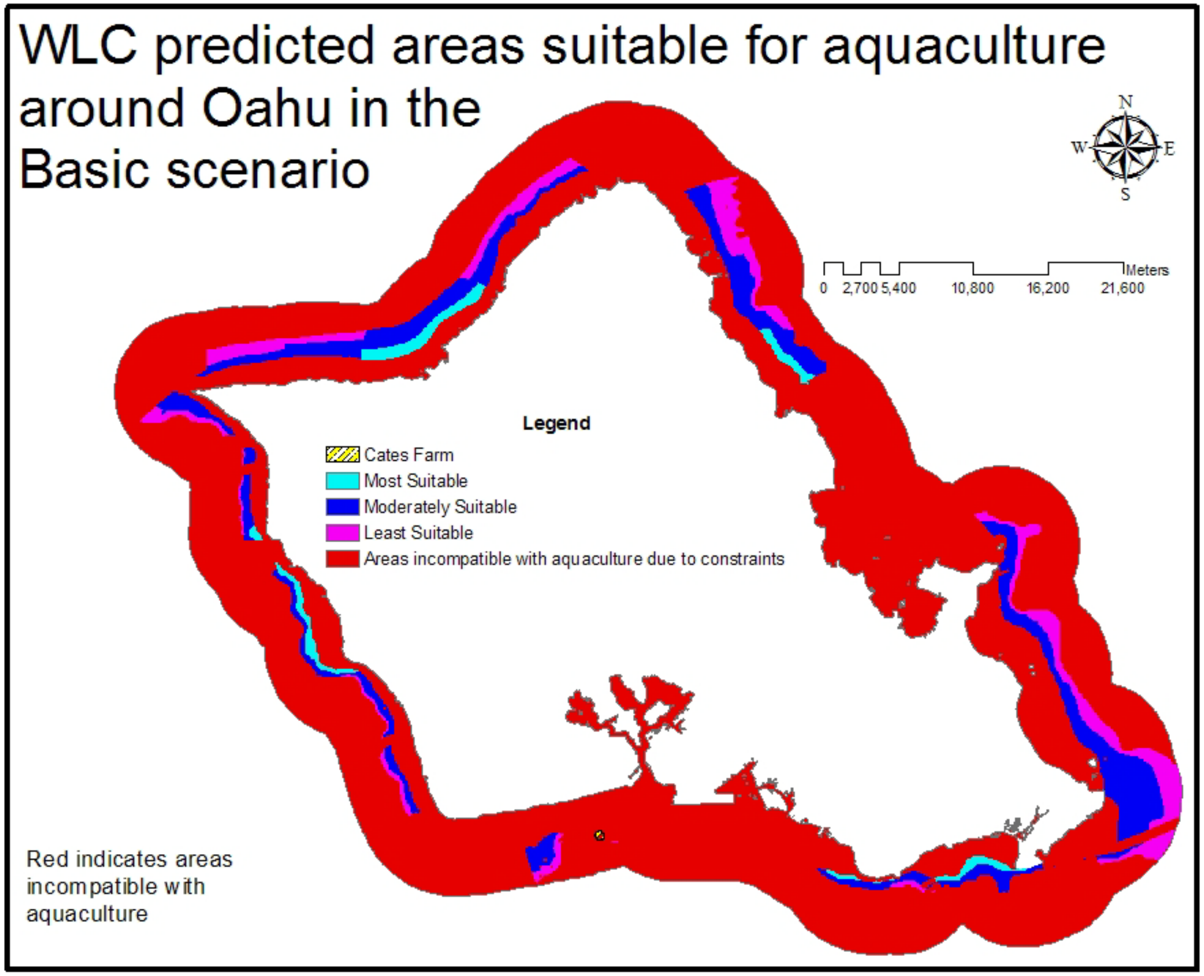

Figure 25 Predicted suitable areas for offshore aquaculture based on environmental and economic parameters at equal value limited to the Basic scenario

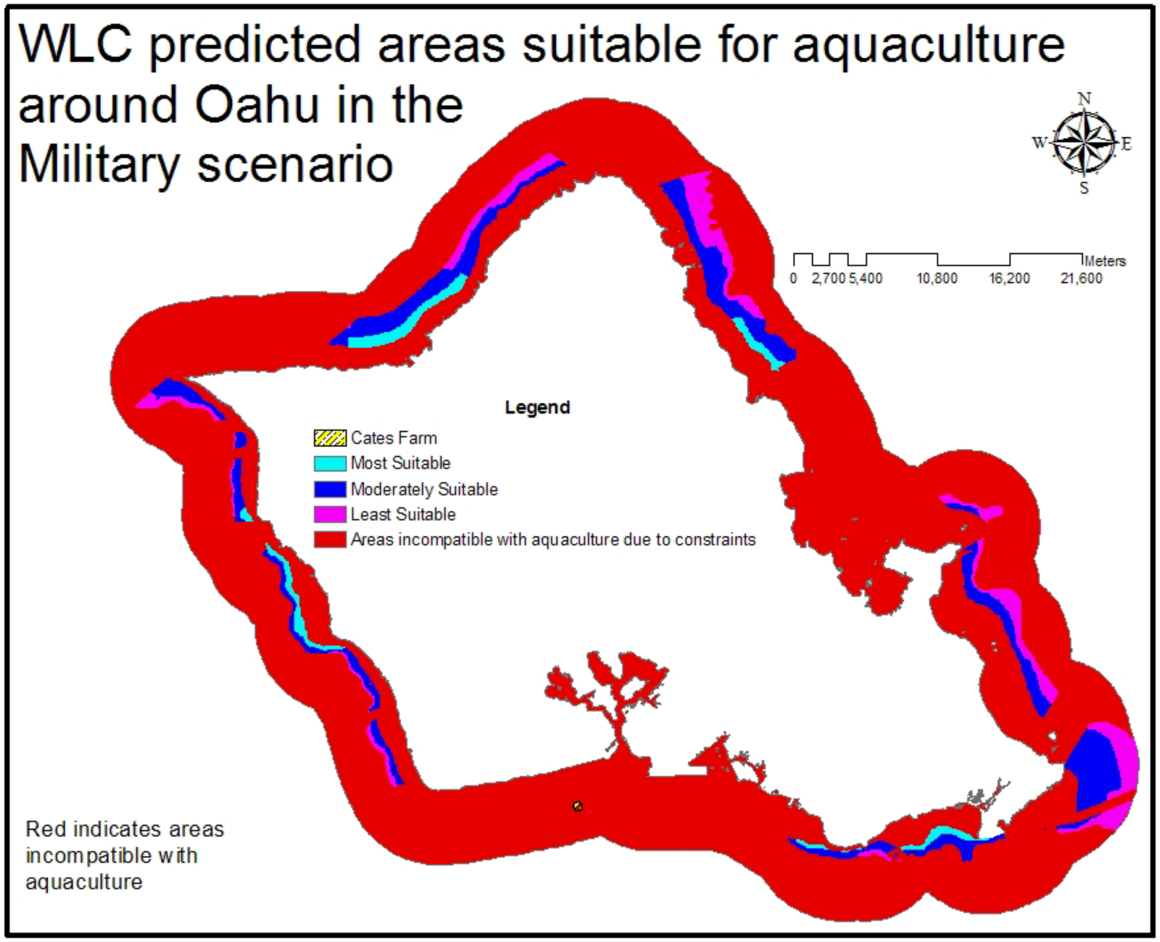

Figure 26 Predicted suitable areas for offshore aquaculture based on environmental and economic parameters at equal value limited to the Military scenario

Table 10 WLC predicted areas based on Environmental and economic parameters with equal value in primary 3 scenario

WLC Prediction	Full Extent Size (ha)	Basic Size (ha)	Military Size (ha)
Most Suitable	3,304	2,020	2,018
Moderately Suitable	15,430	11,547	9,524
Least Suitable	8,159	6,643	5,227
Total	26,893	20,210	16,769

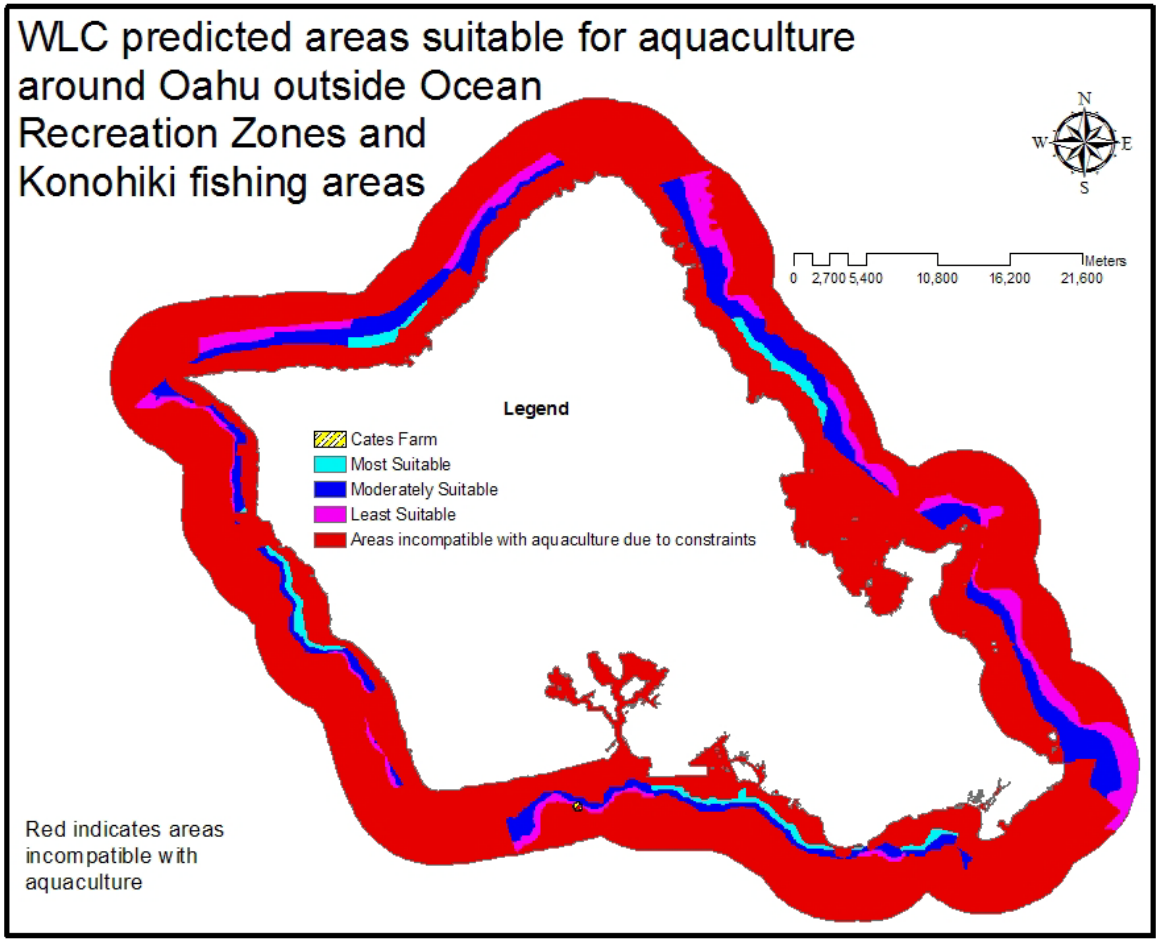

Figure 27 Predicted suitable areas for offshore aquaculture based on environmental and economic parameters at equal values, outside Ocean Recreation Zone and Konohiki fishing areas

Table 11 WLC predicted areas based on Environmental and economic parameters with equal value in primary scenario without possibility of using designated ocean recreation zones or *konohiki* fishing sites

WLC Prediction	Basic(ha)	Military(ha)
Most Suitable	1,471	1,471
Moderately Suitable	9,514	7,656
Least Suitable	6,210	4,838
Total	17,195	13,965

Table 12 WLC predicted areas based on Environmental and economic parameters with equal value in primary scenario without possibility of using *konohiki* fishing sites but using ocean recreation zones

WLC Prediction	Basic(ha)	Military(ha)
Most Suitable	1,521	1,521
Moderately Suitable	9,800	7,942
Least Suitable	6,458	5,086
Total	17,779	14,549

Table 13 WLC predicted areas based on Environmental and economic parameters with equal value in primary scenario without possibility of using designated ocean recreation zones but using *konohiki* fishing sites

WLC Prediction	Basic(ha)	Military(ha)
Most Suitable	1,953	1,953
Moderately Suitable	11,095	11,095
Least Suitable	6,395	6,395
Total	19,443	19,443

Sensitivity Analysis

In order to determine the plasticity of the model, a sensitivity analysis was preformed. As mentioned previously, there was a lack of published data concerning the importance of bathymetry and distance in terms of weighting preference. As the original model is run using equal weights, it was determined that testing the effects of different weights for both inputs was the most appropriate method.

The results of the sensitivity analysis indicate that the model is sensitive to alterations in weight changes to the various inputs. As would be expected the total area does not change. This is important since it indicated that the model is analyzing the same data. When the Bathymetry was weighted more, most suitable and least suitable zones appear at the sacrifice of moderately suitable zones. With Distance weighted more there is an increase in most suitable areas with a decrease in both moderately and least suitable zones (Table 14). These results indicate that the model provides reasonable results and can be used

Table 14 Sensitivity Analysis of predicted area in ha with different weights compared with equal weight results obtained in the Military scenario

WLC Prediction	Equal (ha)	Distance 75 (ha)	Bathy 75 (ha)
Most Suitable	2,018	3,424	4,467
Moderately Suitable	9,524	8,222	6,928
Least Suitable	5,227	5,123	5,374
Total	16,769	16,769	16,769

Chapter 7 Discussion

The ability to use publically available data within a simplified model-space supports sustainable development of aquaculture in places where it was perhaps not previously considered. A simplified model allows users to efficiently, inexpensively and easily identify and reject areas for consideration for use as aquaculture zones. This ability to exclude certain areas that conflict with aquaculture can reduce the time and financial strain associated with collecting more information that is detailed over large geographic areas.

Model Success

The results from the model indicate that it successfully predicts areas as suitable near the current location of the existing farm operation. Though the model output does not directly specify the location for the Cates cage, the cage does overlap both the bathymetry, distance and a valid zone determined to be compatible with aquaculture. Given the 10% to 25% error rate inherent in GIS analysis (Heywood *et al.* 2002), this indicates that the model provides a suitable baseline for future detailed site selection operations.

Induced Error

Most data in GIS models are represented in a raster format. Rasters are analogous to pixels in a modern digital camera. They are square units of various sizes that are determined by the data and the user. When converting a continuous shape such as a curve from a polygon file to a raster, a certain level of error is created. This error is an edge effect and greatly depends on the cell size of the raster. The smaller the cell size, 1 ha in this case, the smaller the error and edge effect as the higher number of cells fit to the curve better. This decrease in raster cell size is subject to the concept of diminishing returns, as the higher the cell count (smaller raster cell size) also increases a file's size and thus increases computational time and costs. Additionally, even with a smaller cell size, there will always be an error that is based upon the accuracy of the original data. There are few GIS data that are exact and true to real life; some are however better than others. When using GIS it is important to remember that it is an approximation (just as is any 2 dimensional paper map or 3D globe) of reality. The planner has to produce policy and management techniques with the understanding that the ground reality may be somewhat different from what is presented in the GIS output. Any rendering of reality introduces errors that create differences from that original reality. Depending upon the data source, errors can be as large as 10% or more (Heywood et al. 2002)

Within the minimal dataset model created here, there was a difference of $30m^2$ between the polygon representation of the 3 mile nautical boundary around O'ahu and the raster representation of the same area. Considering that the area in question is over 1 billion square meters, a loss of 30 meters is quite acceptable.

The use of Natural Neighbor interpolation has been well established as a way to fill in gaps where data is not available, particularly in areas where ground truthing via direct measurement is impractical (Abramov and McEwen 2004). It uses points for which data is known immediately surrounding unknown points to weigh and fill in the missing data. As it uses existing data from within the dataset, it requires no input from the user and leads to a more natural and accurate interpolation of the data (Watson D. 1992). The bathymetry around O'ahu provided by the State as well as the most modern SOEST dataset has gaps within the depth soundings which are best filled by interpolation (Figure 27 and Table 15). As there is uncertainty within the original quality of the datasets, in order not to exclude any potential areas and to select the most appropriate areas, it is better to fill in gaps within the datasets. The approximations created by the interpolation can and should be ground-truth via direct measurements in the areas that are identified as having potential for development.

There is a substantial difference between the State and SOEST bathymetry datasets. Though some of this discrepancy can be attributed to the interpolation of the coarser older dataset, some difference in the proportions can also be attributed to the increased accuracy found in the finer resolution SOEST bathymetry. The older datasets were considered an approximation for digitized navigational maps that are available for all coastal regions. As the most modern SOEST bathymetry cruises have not been completed for all coastal regions where this framework may be utilized, the use of a coarser interpolated bathymetry showed that the framework is viable in data poor environments.

Constraints

Basic

The data that constitute this scenario are included due to their incompatibility with offshore aquaculture. If this model were to be transferred to another location in the world, then the information in the Basic layer would be different. All the areas included in the Basic layer are those that have been identified as somehow conflicting with the exclusive use requirements of offshore aquaculture operations.

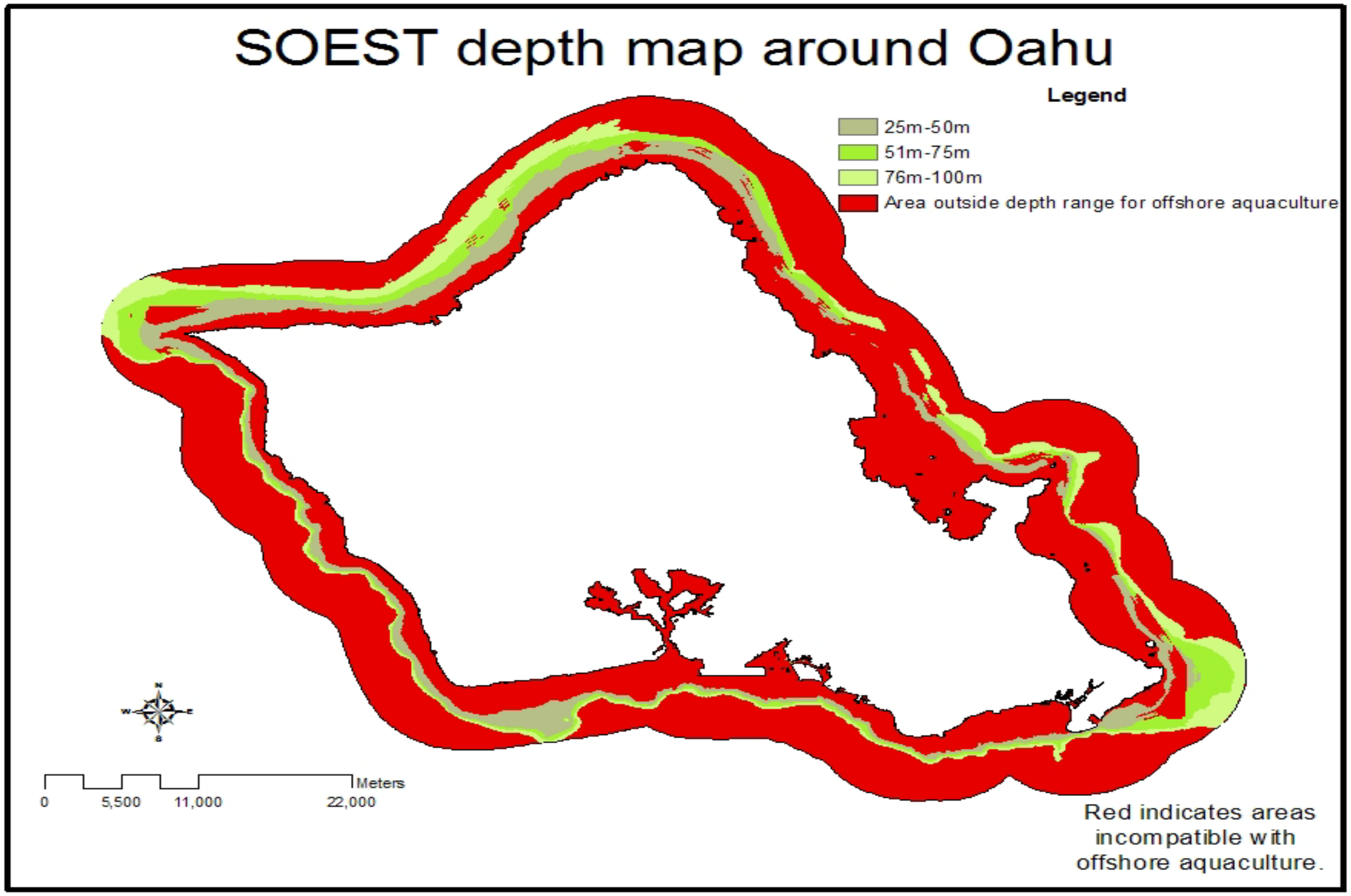

Figure 27 SOEST non-interpolated bathymetry around O'ahu, note the gaps within the known depth layers around the SE, E, NE and NW shores

Table 15 Difference in areas between interpolated and non-interpolated bathymetry data around Oahu

Depth (m)	**SOEST Non Interpolated Bathymetry (ha)**	**Natural Neighbor Interpolated Bathymetry based on State provided coarse Bathymetry (ha)**
25m-50m	44,767	12,077
51m-75m	33,792	9,313
76m-100m	34,376	10,634
Total	112,935	32,024

If this model were to be transferred to an area with significant rivers and fjords which were home to a protected native species then an appropriate buffer should be identified and that data included in the Basic restrictive scenario. In the case of O'ahu, this takes the form of the NOAA navigational chart coral reef maps. Even though the coral represented in this layer are based on data that is 100 years old, it provides a complete perspective around the island, which some newer datasets do not. As with the bathymetry data most regions where this model could be applied will have navigational charts with coral reefs listed, but they may not have high quality, up-to-date benthic surveys. There are still differences between the modern benthic survey and the NOAA navigational chart used in this study. The benthic survey identifies 1,411 more hectares of coral than the navigational chart (5,654 ha and 4,243ha respectively). The location of these coral does vary, however, as this model focuses on offshore aquaculture areas (where coral is sparse), there is minimal overlap of coral in the depth zones required by offshore aquaculture. If this model were to be applied to a nearshore operation then it would become more important to ground-truth the location of coral in the areas predicted as viable zones for aquaculture. As with all the restrictive areas in the Basic scenario, these are current social restrictions such as undersea cables, sewer lines and buoys (a complete list was identified in Table 4). If the State were to choose to set offshore aquaculture as the highest priority, then the area represented within the Basic scenario would change, and undoubtedly, more area would become available.

Military

The addition of the military restricted zones to the Basic scenario induces a further loss of available area to less than 60% of the total area (Table 5). These military areas are actually comprised of several military zones with different uses. The State of Hawaiʻi acknowledges that they have the data, however they have chosen not to publically release it, hence details of what comprises a military zone will not be discussed herein.

As with the Basic scenario, the Military scenario represents social constraints that can change. The military demands on an area are not fixed and with future renegotiations, and changes within the military stance, some areas that are currently identified as military use, may become available. To date, no publically available records of shifting the current military zones have been identified; if they were, the model could be rerun with the new data and provide new results.

Environment

In a minimal dataset model, the ability to select the most influential parameter is crucial. As sustainable aquaculture utilizes native species many of the environments present locally should not be limiting factors in site selection. The native species is adapted to local environments. If it is a species that migrates with the seasons or a sessile organism, (both of which are factors that can be addressed via proper management) then many of the environmental factors that are included in the small-scale GIS models such as temperature, salinity and turbidity become less important. Migrating species should only be cultured in seasons when it was appropriate and the sessile organism is best cultured using nearshore technologies.

A priori determination of the culture system as well as the species simplifies the model further. In this particular case, offshore aquaculture was chosen. Offshore aquaculture is placed in depths greater than 25m. If a nearshore system were chosen, then the depths would have been limited to between 15m and 30m (Ocean Spar 2009b). Most of aquaculture technology is built to robust standards. The offshore cage can withstand category 4 hurricane winds, unlimited fetch, currents of up to 2.5knots, and a storm surge of 6 meters above normal (Ocean Spar 2009b). Consequently, for a first pass model environmental effects such as wave height, current, and wind become less important. Valuable data such temperature, turbidity, and salinity are expensive to gather, and often not available on the scales required for island-wide analysis. These type of data, while providing a more detailed and specific site prediction within a model, are best collected and utilized in smaller areas (Radiarta et al. 2008). The purpose of this minimal dataset model was to identify those areas that are compatible with aquaculture at fundamental level. These areas are appropriate for the more detailed and expensive data collection that would allow further refinement of the selected areas. Various climate models including wave height are being created, however state of the art modeling technology is not as accurate as direct measurement, nor is it currently available at a resolution that is useful even in a regional scale focus. The current cell size for modeled technology is 250 miles square. This does not provide the level of resolution that is appropriate for regional scale site suitability, let alone site selection, and thus these models are not considered (Potemra 2009).

As the cage that houses the organisms is allowed to float 10m beneath the surface, the actual depth of the anchoring mechanism is only limited by the resources available to the farmer. Cable and anchoring systems can become cost prohibitive at greater depths. At deeper anchoring depths for an operation, more cable and more expensive and highly trained divers are needed to service the cages. Slope is also not a factor as various anchoring technologies are available and examples of cages being anchored to vertical walls exist. Again, this becomes a cost factor for the operator; the easier the slope and bottom type the cheaper the initial installation and maintenance (Ocean Spar 2009b).

In general, for a minimal dataset model based on publically available data, it is the assertion of the author that the most appropriate and valuable data layer is depth. Consequently, 3 depth ranges were chosen and for most suitable locations a depth between 25m and 50m was indicated. Even though 50m is just beyond the level allowed for recreational divers, ground truthing of the area can place the cage in depths accessible to recreational divers. The moderately suitable depth category ranged between 51m and 75m. This depth range requires specialized divers, but the additional costs of cabling are not as pronounced. The least suitable depth range for offshore aquaculture was between 76m and 100m. These depth ranges require both specialty divers and extensive cabling. However, if the farming operation has deep pockets then this is still suitable. Beyond this depth is not appropriate to consider an anchored technology, and floating offshore aquaculture installations are still being developed (Gomez 2009).

Within these limitations of depth, there are still extensive areas around Oʻahu available, with the highest area being available in least suitable depths, followed closely by moderately suitable depth ranges. The smallest area was the most suitable depths of 25m to 50m. These results are a function of the geology of the island. Within the basic and military scenarios, the spread of suitability remains the same; however, the available area drastically decreases. The basic scenario represents a mere 1.27% of the total area limited by depth, while the military scenario represents 1.06% of the total area in the 25m to 100m depth range. This indicates how truly restrictive the social constraints on offshore aquaculture around Oʻahu are. A smaller area however allows for further detailed analysis in later models.

Economics

There are numerous economic considerations for offshore aquaculture. Many of these costs are not geospatially limited. The most appropriate geospatial economic consideration is distance from onshore support facilities. As the exact location of a shore-based support facility us unknown, the location of harbors becomes a valid proxy. The reason for this is that the support vessels have to be docked. There are two types of offshore support vessels, large and small ones that travel at 15 and 9 knots respectively (Sims 2008).

Labor costs are one of the highest costs associated with aquaculture (Leung et al. 2002). At greater distances from a harbor, the cost of idle workers as well as fuel and wear and tear on a boat increases. Zones around each harbor were created with 3 concentric rings representing 1-3, 4-6, 7-9 nautical miles, and those categories were again expressed as most through least suitable. The closer a farm is to a harbor, the lower the economic costs associated with an offshore installation thus it was considered the more suitable. The more distant rings became moderately and least suitable. Outside of the 9 nautical mile zone were areas which were not considered.

The areas of moderate suitability were found to offer the most area around Oʻahu, followed by most suitable and the least suitable. This distribution if different from the depths and is likely a function of the placement of the harbors and the geography of the coastline. Within the basic and military scenarios the total area are 68% and 57% of the total area available. This difference in percentages is a function of the location of harbors. If a harbor were to be located in an area with more military restrictions for example, then the economically viable areas would again be reduced. Conversely, if there are harbors located in areas that do not have either Basic or Military restrictions, then more zones are economically viable.

Social

There are numerous considerations that can be included for the social acceptability of aquaculture sites. Depending on what data is locally available, this portion of the model will change. Social consideration can range from State designated zones including alternative economic uses of an area, such a designated fisheries, to recreational uses such as surfing sites. They can also include culturally significant areas that are not officially recognized by the State, but have significant cultural meaning for the local community, such as traditional fishing zones.

In the case of the current minimal dataset model around Oʻahu, two social considerations were included. The first was the State designated recreational zones. This particular dataset was the most appropriate dataset available publically. It contained polygons of areas designated by the State of Hawai'i as officially recognized recreation zones. Though other data layers exist for sailing, sport fishing, and body surfing sites, these layers are all point format data and also carry no official recognition within the Statues of Hawai'i. No standard definitions have been published regarding the size of buffer that one could use to define a body surfing site, and to limit a sailing site to a point data is not geospatially viable. Though the boundaries of body surfing sites could be extrapolated based on shore break (benthic information) this varies seasonally and would add an added dimension of error. There have been no publications indicating that the State would re-designate the boundaries of the recreational zones. Consequently, the analysis compared suitable areas either with or without the recreation zones. There are over 13 thousand ha located in recreation zones around O'ahu (identified in Table 8). Within the basic scenario over 10,000 ha are lost, leaving just over 3,000 ha of recreation zones that may compete with offshore aquaculture uses or 25% of their total area. Interestingly, there is no difference in total area between the Basic and Military scenarios. This lack of difference indicates that no recreational zones are located within military designated areas. This makes logical sense, as a military restricted zone should not be filled with recreational users. This lack of difference also provides the first verification of the model concept. The 25% that can conflict with offshore aquaculture operations is a relatively small number, which should allow for negotiations to be made between the potential operators and the local communities.

Traditional cultural uses are highly important considerations in any area with a native population. No such cultural data exists for marine environments around O'ahu. However utilizing a 60 year old territorial publication, traditional restricted fishing areas were identified for O‘ahu. These areas correspond fairly well to the State provided *ahupua‘a* data layer. A total of 39 offshore *konohiki* areas were identified and digitized, representing over 17,000 ha in area (Table 9). Within the Basic and Military scenario, a total of 55% and 52% of these *konohiki* areas remain that may conflict with offshore aquaculture. There have been no recent publications of the current uses of these areas by the communities. However knowing of such sites allows the model to predict total area potentially lost by the community and thus facilitate greater discussion and potential for compromise (and acceptance of an aquaculture operation by the local community).

Combined

There are very few places around the island of O‘ahu that are viable and meet all the requirements of the model. The WLC predictions within the general scenario are all limited to less than 20% of the total available area around the island.

This however was not an exercise to predict areas around O‘ahu for aquaculture. It was recognized that the most populated island in the State of Hawai‘i, would predictably have the most restrictions and hence fewest available sites. The point in developing the model was to determine if a minimal dataset model could accurately predict an offshore aquaculture site location based on a standardized, limited set of inputs.

To that end, Figure 28 represents the most accurate piece of data within the model, the geographic coordinates based on latitude and longitude of the currently operating Cates International offshore m*oi* aquaculture facility. The precise location of the farm is not directly in an area predicted by the model.

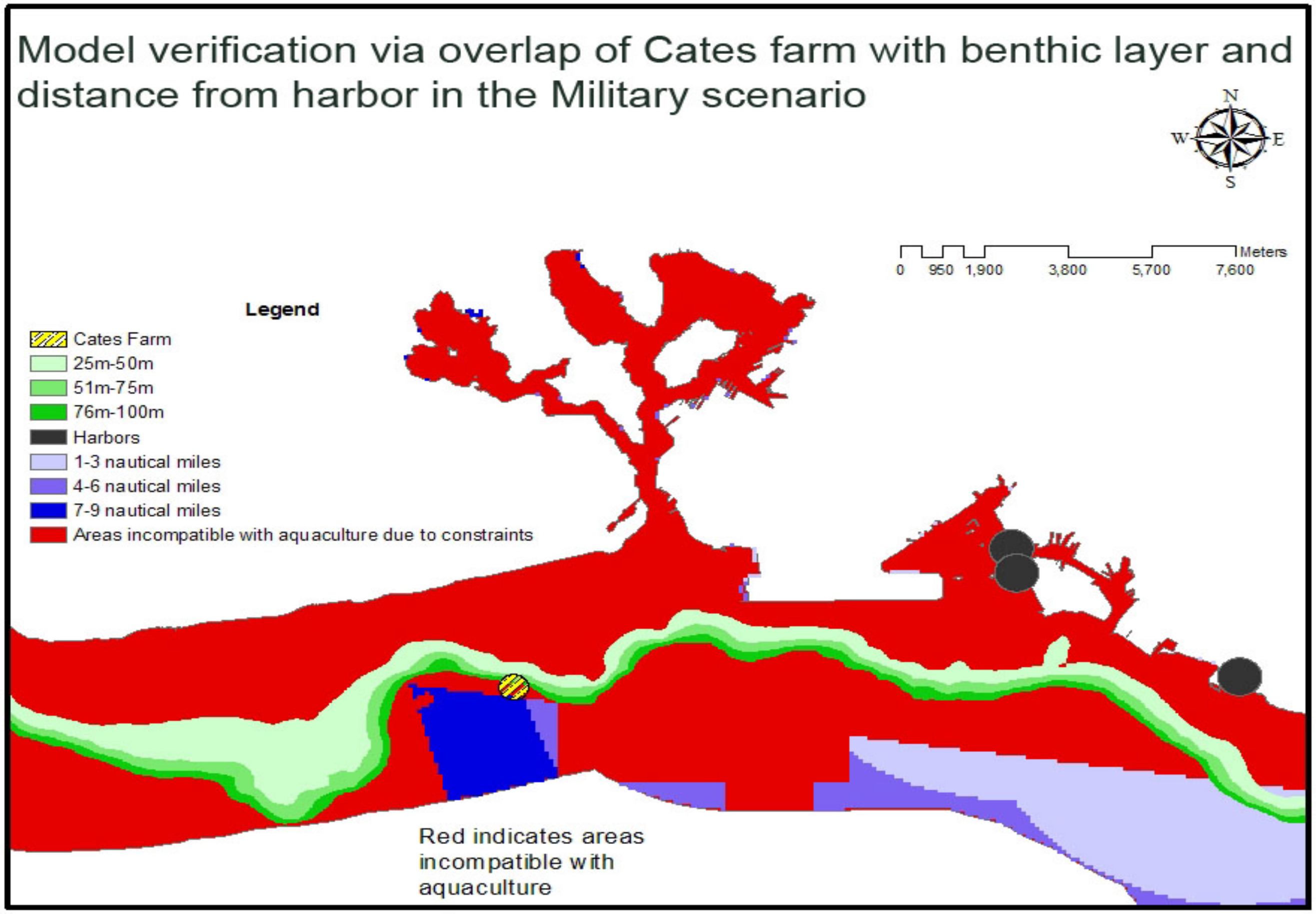

Figure 28 Location of Cates Aquaculture farm south side of Oahu, Note that the area is overlapping both a predicted depth and predicted distance from harbor within the more restricted Military scenario, thus verifying the model.

However, the location does overlap the most important data layers. It is within a predicted depth zone (fulfilling the environmental requirement). The farm is also within a predicted economic zone (fulfilling the economic requirement). Lastly, it is overlapping an area within the most restrictive Military scenario. Given the accepted 10% error within GIS data (Heywood et al. 2002), this overlap helps to verify the model and the output it generates. By identifying general sites that have potential for aquaculture, the results could be further refined through more detailed data collections to further identify the most sustainable sites for aquaculture. The presence of the Cates farm overlapping areas that are within the acceptable ranges of the environmental economic and socially limited areas support the premise, that including the economic and social data would generate an output that was more accurate than utilizing environmental parameters alone. Again, the inclusion of purely social consideration of recreation and traditional use areas did not have as large an impact on the model as either environmental or economic parameters. Socially useful areas such as recreation zones and traditional use sectors are an important addition to the model, and must be considered to facilitate acceptance of aquacultural development. A caveat to using the Cates location as verification for the model is that the current location may not have had as rigorous a selection process in its development. The location was first a University of Hawai'i testing facility which was designed to determine the viability and environmental impacts of offshore aquaculture. The use of the site as verification is still useful as the Cates operation is economically viable and has not had difficulties with environmental pollution.

Compared with the previously mentioned GIS studies on small well studied and understood areas, this model, listed last, is best compared to the larger scale regional models presented in Table 16, where 'x' designate data not incorporated in a particular model (Levings et al. 1995). Regional scale models in a marine environment also have limited data available, and the minimal dataset model has most of the elements present in the larger regional scale models that have been vetted and accepted by various governments around the world.

Data Quality

The model used for this analysis specifically utilized older datasets for the bathymetry. Not all places where this model may be utilized will have the benefit of precise high resolution bathymetry data. Additionally there may be gaps within the bathymetry that is available. By utilizing the State provided "J Smith bathymetry," which is based on sounding points that are 250m from point to point, the model indicates a resilient nature in providing a general schema of results which can be further analyzed in greater detail. The natural neighbor interpolation technique was used to fill in gaps within the data.

Previously presented Table 15 represents the areas of depths using the more accurate, and non-interpolated bathymetry compared to the interpolated coarse resolution bathymetry.

Table 16 Environmental and social data in aquaculture site suitability models compared with the minimal dataset framework (x indicates data not included) (Levings et al. 1995)

Area	*Site Boundary*	*Min Depth*	*Distance between farms*	*Distance from critical habitat*	*Distance from Ecologically sensitive area*	*Oceanographic*	*EIS or Similar*	*Zoning criteria*
Maine	x	x	x	>402m	>402m	x	prohibited in 'pristine areas	prohibited in 'pristine' areas
New Brunswick	>45m	>2 or >8m	>300m	>300m	prohibited in designated ecologically sensitive area	limited by winter temperatures	x	x
Ireland	x	x	>1000m	>1000m	considered'	not in areas where currents <0.1m/s	yes if annual production >100t	yes must be designated
Washington	x	depends on species	x	>91m	considered'	depth, production, currents	yes	shoreline management act
Norway	x	>20m	x	distance form mouth of salmon rivers	prohibited in certain fjords	Lenka	x	Lenka
Scotland	x	x	>8000m	>500m	x	catalog of characteristics prepared	yes in outer lochs, farms >6,000 m^2 on open coast	prohibited in 'sensitive' areas
British Colombia	x	20m	>3000m	125m	considered'	accounted for in biophysical rating scheme	yes	CRIS
Iceland	x	x	>2000m	5000-15000m from mouth of salmon streams	x	x	x	x
Oberding Minimal Dataset	x	25m	x	30m from MLCD	30m from coral	limited by culture technology	yes	State and Federal Regulations

The total area between 25m and 100 around O'ahu within the non-interpolated fine resolution data is 112,935 ha, while the interpolated coarser resolution is 32,024 ha. The increase in area appears to be due to the increased quality of the new soundings. The bathymetry is left non-interpolated for an example of how interpolation of older data enhances the models results in areas without access to high quality bathymetry.

Table 17 and Figures 29 through 31 represent the areas predicted by the WLC in the 3 general scenario comparisons. Once the WLC is completed using the environmental and economic data, there is little difference between the coarse interpolated data and the fine non-interpolated SOEST data in terms of total area available. In the Basic scenario the WLC based on SOEST bathymetry actually predicts more area available in general than the interpolated coarse bathymetry. Within the WLC modelscape, the differences between the two bathymetries are not substantial overall. This lack of difference suggests that interpolated coarse bathymetry is just as useful as a predictor of potential sites for further research as high definition style fine detailed bathymetry. This confirmation allows the model to be used successfully in areas which may not have access to the latest (and costly both temporally and monetarily) bathymetry data.

Table 17 WLC prediction comparisons using interpolated vs. non-interpolated bathymetry and the percent difference in area between the three scenario

WLC Prediction	State Total (ha)	SOEST Total (ha)	State Basic (ha)	SOEST Basic (ha)	State Military (ha)	SOEST Military (ha)
Most Suitable	3,304	3,219	2,020	2,129	2,020	2,129
Moderately Suitable	15,430	14,964	11,547	12,144	9,532	9,671
Least Suitable	8,159	8,476	6,643	7,143	5,231	4,496
Total	26,893	26,659	20,210	21,416	16,783	16,296
% Difference	100	99	100	105	100	97

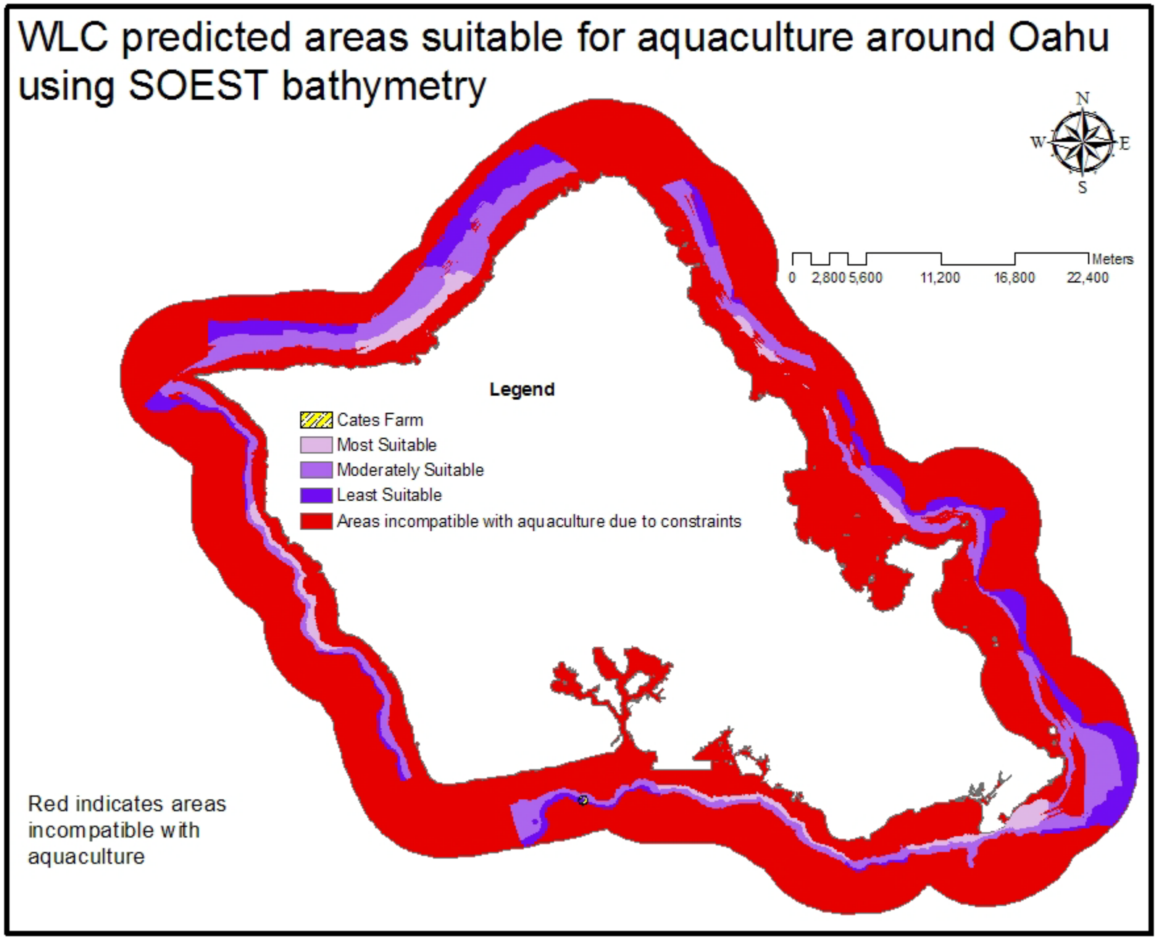

Figure 29 WLC predicted areas around Oʻahu using non-interpolated SOEST data

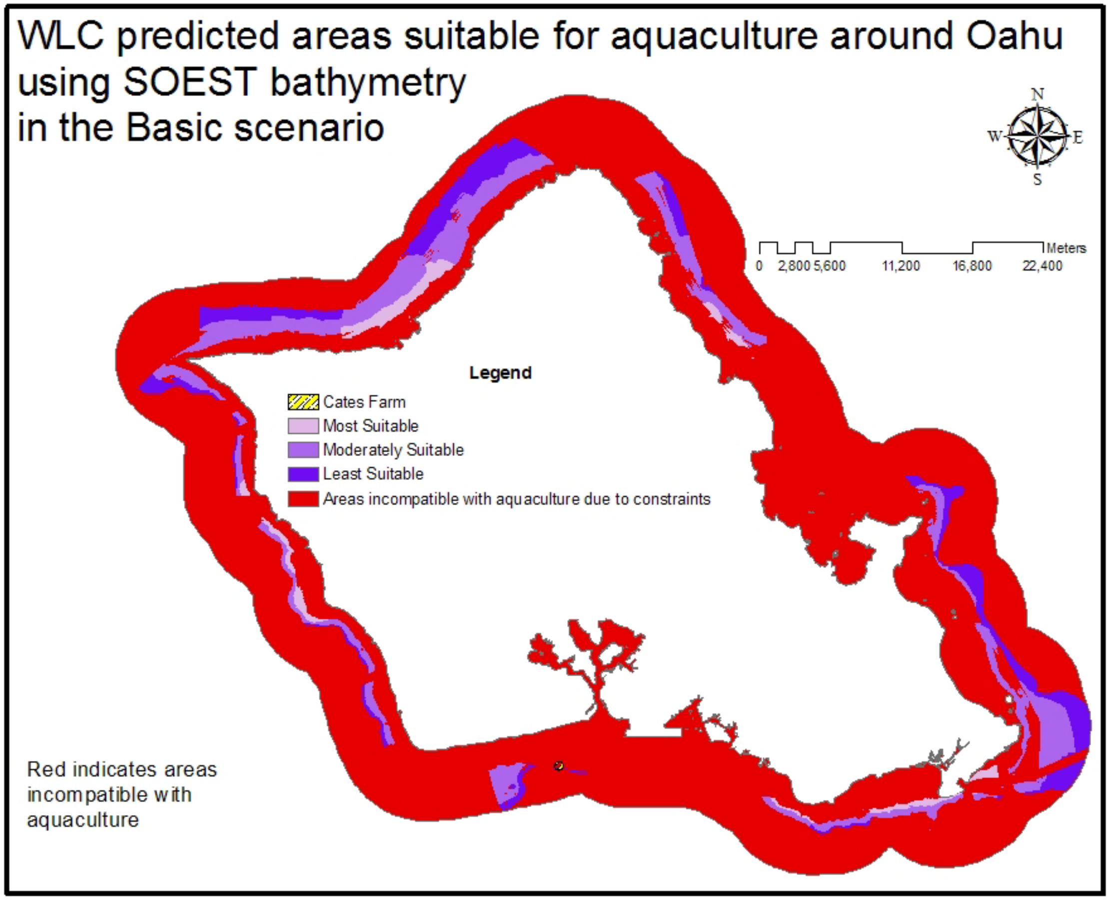

Figure 30 WLC predicted areas around O'ahu using SOEST non-interpolated data within the Basic constraint scenario

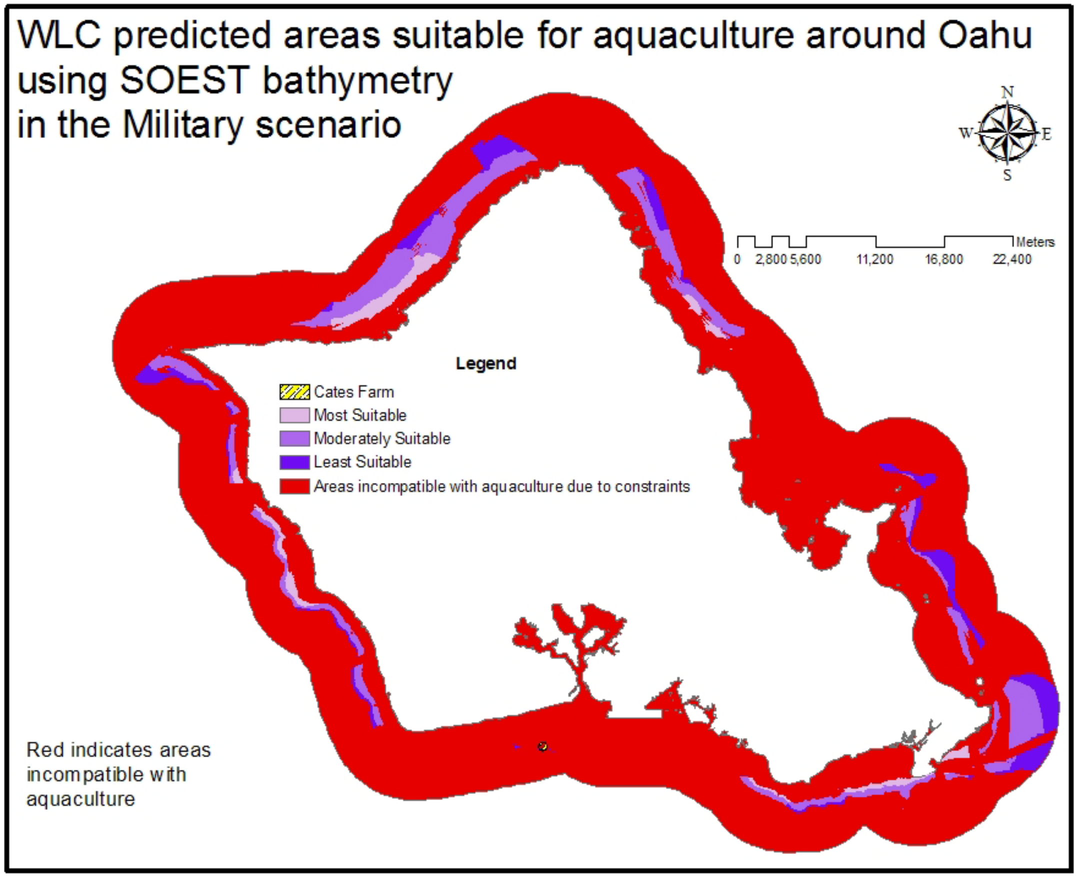

Figure 31 WLC predicted areas using SOEST non-interpolated bathymetry with the Military constrain scenario

Chapter 8 Conclusion

The current model has shown itself to be a simple and inexpensive method for rapidly determining areas to be considered for aquaculture development on the island of O‘ahu. It allows the user to minimize the complex and often expensive secondary data collection to a limited number of areas. More importantly it allows users to pre-determine areas which are not compatible with aquaculture.

By accurately predicting a site where current aquaculture operations are taking place, the model has been verified. The location of the Cates offshore aquaculture facility overlaps all three important factors, depth, economic zone and an area predicted viable in the most restrictive Military scenario. This robust nature and simplified minimal dataset requirement of the model will make it a useful tool for identifying areas interested in development of marine aquaculture with little access to highly detailed scientific data.

By changing the initial parameters of the model, it could be utilized for nearshore aquaculture site suitability analysis as well. A mere change in the depth requirements from 25m-100m to 15m-30m will create a completely new set of outcomes. This change to a nearshore system will also create an overlap (and thus increased competition for space) with recreational users as well as potential competition with traditional uses. However, with the results from the model, a more informed debate can result between the diverse groups. Due to the simplified nature of a minimal dataset model, all groups should plainly understand the results without requiring extensive knowledge of either GIS or modeling.

It is my belief that this model is robust enough to be utilized by regional and environmental planners to assist in the development of offshore cage aquaculture in any coastal area. As mentioned previously, the publically available nature of the data minimizes time and costs associated with using this first phase model. Within the Coastal Zone Management Process, this model should be implemented early on. The output from this framework will help establish boundaries for other activities and development. The detailed Phase 2 portion of site selection would be implemented later in the CZM process once the boundaries and competing interests have been resolved. As it is a non-complex model, local community groups can also implement it when advocating for their regions.

The alternative method

As this model is designed to be a minimal dataset based on publically available data, the output generated indicates areas of interest for future aquaculture development. Most previous studies of site selection have occurred in highly understood and data-rich areas. With such access to high quality data, highly refined and exact site selection results can be expected. It is this data that should be gathered in the areas predicted by this minimal dataset model that will enable interested parties to further define and pinpoint the appropriate locations for offshore aquaculture.

Suggestions for improving the primary minimal dataset model

The higher quality the data utilized, the more accurate the results. Additionally, if some of the suggested data for the secondary model are available publically on a regional sized scale and with the appropriate level of detail, then the data should be included in the environmental or social section of the model. This inclusion will further refine the results and allow for even more accurate predictions to be made, thus reducing the costs associated with the secondary detailed model. Additionally, current shipping lanes should be included in the original Basic level of the model. These lanes can disrupt the proprietary nature of an aquaculture pen site and thus should be avoided.

The Analytical Hierarchy Process (AHP) (Saaty 1980) was initially considered for developing the weightings on the WLC. During the development of the minimal dataset, it was determined that though the AHP system was more appropriate, due to budget and temporal constraints a sensitivity analysis was conducted instead. The sensitivity analysis is less ideal than an AHP, however it does have the benefit of cost effectiveness and when conducted properly efficiency. The AHP system is useful in situations where there are competing and divergent interests in a limited resource. The AHP allows the user to prioritize the resources based on the input from the competing interests; a potentially equitable outcome is reached by using statistical processes.

The highest resolution data that is available should be utilized. This has traditionally been a major issue for marine environments as they have lagged behind in the quality of remote sensed data as well as models.

Proposed requirements for a site selection framework

This preliminary model focuses on a regional scaled site suitability result. As mentioned it allows for regional planners to incorporate aquaculture into the coastal development plans. The next steps involved feeding the output of this model into a finer scale site selection model.

This will allow the regional planners and environmental managers the detailed control of which areas should be developed and at what cost.

There are several variables which must be included in the site selection model which are not present in the regional scaled model. The first such change is a small raster cell size. It is recommended that a size no larger than 0.05 ha be employed. Even though most offshore cage facilities utilize more than 1 ha, it is important to place the center where the cages and animals are at the most optimal location. The data which should be included for this secondary phase include the following factors:

- Turbidity, the inclusion of which would allow for further species discrimination within the results of the model, as bivalves often have different water clarity requirements from finfish.
- Salinity, different species have different salinity requirements and some thrive better in more nearshore and brackish waters.
- Temperature, water temperatures in tropical regions do not vary greatly between seasons or regions around an island, however within temperate regions, water temperatures can vary greatly, and thus impact the length of a growing seasons, as well as the types of species which can be cultivated.
- Dissolved Oxygen, this is a detailed dataset which can impact the growth and survival of both finfish and bivalves as well as algae, though it is more of a concern in low current poorly flushed bays it can still be a factor in nearshore areas.

- Currents, since these vary seasonally in strength and direction, it is important to have accurate current data for an area to ensure that species and technology are within acceptable levels. Too high a current will flush away food before the animals have a chance to ingest, and they will spend most of their energy on swimming and not growing, thus leading to smaller sized animals on the market.
- Winds and waves are both important as winds can affect waves. Knowing the predominant direction seasonally can allow a model to predict storms which may impact the ability of support vessels and personnel to access the sites and care for the animals and cages.
- Bottom type, depending on currents and the species being cultures, this can affect not only the technology used to anchor a cage but also the impact that the operation has upon the benthic ecosystem.
- Improved social competing restrictions such as recreational areas and culturally sensitive areas, because by better understanding the local social conditions, it is easier it is to avoid conflicts based upon misunderstandings and poor data.
- Viewscapes, the visual pollution associated with aquaculture facilities has been cited as one of the reasons local communities oppose caged aquaculture.

Due to the submerged nature of the modern offshore cage, this may not be as high a valued input; however consideration of such concerns will allow a secondary model to address potential arguments against aquaculture expansion in a particular region. More economic data should also be considered in this next phase. This entails considering distance to shore-based support facilities (assuming that they are not located within the harbors) as well as the distance to markets, including export facilities such as airports, and the sizes of local markets. The parameters should be incorporated into the following models:

$$Enviro\text{-}Biological = \Sigma\ (([biological\ limitation]*x_n) + ([environmental\ limitation]*x_n))$$

$$Economics = (([economic\ consideration_1]*x_1) + ([economic\ consideration_n]*x_n))$$

$$Socio\text{-}Political = \Sigma\ (([traditional\ area]*x_n) + ([current\ use]*x_n))$$

These are all data which a second finer model should include and gather about the areas predicted within the minimal dataset model. As most of this data is important for sustainable offshore aquaculture and is expensive to gather, it is important to limit the areas, and thus limit the cost in gathering this information.

This minimal dataset framework is recommended as a viable tool for site suitability identification. With this easy and inexpensive framework, environmental planners and researchers can quickly identify areas of coastal waters to study in further detail for potential sites of aquaculture operations. The flexibility of using a minimal dataset based on publically available data will allow for valuable research funds to be focused on areas which hold the greatest potential for viable aquaculture operations. This will not only optimize costs but also add to the sustainability of future aquaculture operations.

Appendix A: GIS Layers

Relating to environmental conditions off O'ahu and the Big Island
Data which was previously available (Helsley and Umemoto 2003):

Bathymetry	3- Mile Boundary	Army Corps_Shoals
12-Mile Boundary	Aids to Navigation	Anchorage Areas
Boating Facilities	Bottom Type	Cables
Class Water	USGS <by island>	Coral Reefs_NC
Dumping Areas	Explosive Dumping Areas	FAD Areas
NOAA-NOS <all state>	Fish Havens	MBARI <63 separate files>
Natural Area Reserves	J. Smith (modeled data)	Obstructions
Offshore Installations	Sewer Lines	Unexploded Ordnance
Wrecks	Military-related Areas	Danger-restricted Zones
Original Tidal Currents	Tidal Currents (modeled)	Composite Bathymetry
Prohibited Areas	Small Arms Firing Area	Submerged Submarine Area
Body Surfing Sites	Water Quality Classifications	Coastline
Coastal Resources	Conservation District	Fish Management Areas
Fishponds	Ocean Recreation Areas	Islets
Hawaiian Islands Humpback Whale National Marine Sanctuary	Marine Life Conservation Districts	

Appendix B: GIS Coded Equations utilized within ArcGIS

Basic = ∑([private_sites] + [public_protected_sites])

Military = ∑([military_sites] + [private_sites] + [public_protected_sites])

Environmental = (([Bathymetry]))

Economic = ([distance_from_harbors])

*Comprehensive= ((([Enviro-Biological] * 0.5) + ([Economic] * 0.5))*

The comprehensive model was run within the various constraint scenarios to achieve the outcomes presented.

The sensitivity analysis was conducted using the following equations:

*Comprehensive= ((([Enviro-Biological] * 0.25) + ([Economic] * 0.75))*

*Comprehensive= ((([Enviro-Biological] * 0.75) + ([Economic] * 0.25))*

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