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Article

Development of a GIS-Based Tool for Aquaculture Siting

Noelani Puniwai [1,*], Lisa Canale [2], Maria Haws [2], James Potemra [3], Christopher Lepczyk [1] and Steven Gray [4]

[1] Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, 2440 Campus Road, Honolulu, HI 96822, USA; E-Mail: lepczyk@hawaii.edu

[2] Pacific Aquaculture and Coastal Resources Center, University of Hawai'i at Hilo, 200 W. Kāwili St, Hilo, HI 96720, USA; E-Mails: canale@hawaii.edu (L.C.); haws@hawaii.edu (M.H.)

[3] School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, 2440 Campus Road, Honolulu, HI 96822, USA; E-Mail: jimp@hawaii.edu

[4] School for the Environment, University of Massachusetts, 100 Morrissey Blvd., Boston, MA 02125, USA; E-Mail: steven.gray@umb.edu

***** Author to whom correspondence should be addressed; E-Mail: npuniwai@hawaii.edu; Tel.: +1-808-933-3186; Fax: +1-808-933-0704.

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Abstract: Nearshore aquaculture siting requires the integration of a range of physical, environmental, and social factors. As a result, the information demand often presents coastal managers with a range of complex issues regarding where specific types of aquaculture should be ideally located that reduce environmental and social impacts. Here we provide a framework and tool for managers faced with these issues that incorporate physical and biological parameters along with geospatial infrastructure. In addition, the development of the tool and underlying data included was undertaken with careful input and consideration of local population concerns and cultural practices. Using Hawai'i as a model system, we discuss the various considerations that were integrated into an end-user tool for aquaculture siting.

Keywords: aquaculture; coastal; GIS; Hawai'i; marine spatial planning; scale

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1. Introduction

1.1. Aquaculture and GIS

Rapid coastal development has increased concerns of sustainability and the compatibility of the multiple uses of marine resources. In particular aquaculture development, like other ventures that involve the use of public lands or resources, is seeing a rush of development interest, yet is subject to a complex and often confusing system of regulations at local, state and federal levels [1]. Because coastlines are transition zones between terrestrial and marine environments, they have unique challenges both because of their physical nature and the way in which they are used and perceived by people [1,2]. Although frameworks that integrate the necessary biological, physical, and social dimensions for facilitating aquaculture planning exist, there is a lack of knowledge associated with the scale of these datasets, case studies that identify barriers to public decision-making, and how Geographic Information Systems (GIS) approaches can provide decision-support to resource managers, aquaculture industry representatives, and local community stakeholders.

The recent increase in aquaculture development is driven by large external factors such as population growth and an increased demand for protein, coupled with no efforts to slow fishing pressures across the world's wild-capture fisheries. By 2050, Food and Agricultural Organization [3] estimates global population will reach 9 billion people, requiring a 60% increase in food production [3]. Although food consumption has risen, the amount captured through fishing has been stable for the last 20 years, with aquaculture providing 47% of all fish consumed, highlighting the role aquaculture has played in supplying the additional fish protein needed to meet growing demand. This growth in demand has been facilitated through substantial advances in recent years in breeding technology, system design, and feed sources [4,5].

Although aquaculture production around the world is expected to increase along with the human population, the economic, social, and environmental benefits and costs of aquaculture continue to be debated by a broad range of stakeholders. Even with technological gains, such as refined fish welfare techniques and reduction of input-heavy production, many environmental, indigenous, and marine stakeholders worry about access, tenure, and sustainability of the resources [6]. In fact, many stakeholders believe that the costs of aquaculture development are internalized locally and not felt by communities that consume the farm-raised species [7–9]. One common issue often cited by local community groups is aquaculture's negative environmental impacts, particularly with marine and pond-raised fish farming [5,10]. Cage farming can potentially result in waste offloads, introduction of alien species, genetic interactions, disease transfer, release of chemicals, use of wild recourses, alterations of coastal habitats, and disturbance of wildlife [11]. Similarly, environmental health risks associated with aquaculture may include elevated levels of antibiotic residues, antibiotic-resistant bacteria, persistent organic pollutants, metals, parasites, and viruses in finfish and shellfish [12]. Environmental benefits, on the other hand, are mostly seen in the reduction of fishing pressure on these specific stocks due to the availability of farm-raised species as well as other commonly caught species. Understanding these costs and benefits, are further complicated for management agencies given regulatory permitting, and jurisdictional issues and who receives the benefit of development, taxes, and increased revenue.

In addition to reducing pressures on wild caught fish populations, research has also shown that there are a number of economic benefits associated with aquaculture, especially for communities in remote and rural regions [13]. For example, assessing the benefits of two different scales of aquaculture, Bergquist (2007) showed that small-scale aquaculture provides greater benefit to local communities while large-scale shrimp aquaculture has larger short-term benefits as well as environmental costs [8]. Understanding how these costs and benefits exist in a spatially explicit manner is important when outlining the potential for aquaculture growth, and more importantly, in discussions with local decision-makers and where and how to implement aquaculture in different areas.

As a way to provide some decision-support to the complex issues of aquaculture and coastal planning, GIS is often used as a tool to develop spatially explicit approaches to natural resource decision-making scenarios [14]. In the case of coastal areas, GIS can be used to balance divergent interests and has been applied in a variety of contexts including aquaculture, energy production, conservation, fishing, and recreation [15]. For instance, GIS has been used to comprehensively assess and direct aquaculture development worldwide, both inland in ponds and reservoirs, and in coastal areas in Ireland and China [16]. These examples required both sound scientific knowledge of species and habitats and an effective GIS geodatabase that provides the spatial component to integrate biophysical and socio-economic characteristics [14]. However, data products that can support aquaculture decision-making across multiple stakeholder interests are generally unavailable, with the ones that do exist often developed for a specific client, thereby limiting the use of GIS as data product that can be used by a range of different stakeholders. Furthermore, there are a number of drawbacks that have limited the usefulness of GIS data products to date, including: (1) the amount of technical expertise required; (2) poor levels of interaction among GIS analysts, subject matter specialists, and end users of the technology; (3) continuity of GIS products and results; (4) communication of results back out to the community; and (5) the disconnect of researchers from the actual systems under study [17,18]. Although such limitations have been identified, there is a need for GIS to play a larger role in enhancing the participation of community members in management decisions. Given such need, the goal of this study is to understand the benefits and limitations of using GIS in understanding aquaculture siting on the Island of Hawai‘i in the context of marine spatial planning, integrating biophysical, regulatory, and social aspects.

1.2. Case Study: Aquaculture in Hawai‘i

Aquaculture in Hawai‘i offers an ideal case study to look at the complexity that surrounds aquaculture planning and the creation of GIS data that can be used by a wide range of stakeholders. Like many island communities, there is growing interest at the local, state, and federal levels in developing the aquaculture industry as it is already a significant contributor to the economy with more than 100 aquaculture farms in the State. Hawai‘i County, located on Hawai‘i Island, hosts about 75% of total aquaculture production in the state, with a highly diverse assemblage including ornamental freshwater and marine fishes, off-shore cage culture, two of the largest bivalve (clam and oyster) seed production facilities in the state, algae culture for food and nutraceuticals, and abalone. The aquaculture sector of Hawai‘i Island is also unique since it was one of the pioneering sites for the off-shore cage culture of marine finfishes (Kona Blue Water, Inc., Kailua, HI, USA) as well as hosting some of the

most technologically advanced farms in the U.S. In addition, given its unique marine environment, aquaculture production in Hawai‘i County has the potential to utilize its 266 miles of coastline for off-shore cage culture of marine fishes, off-shore and near-shore culture of invertebrates (e.g., bivalves), culture of macroalgae, and production of non-food products (e.g., pearls), biofuels and nutraceuticals.

Future expansion of aquaculture in Hawai‘i presents managers with complex issues regarding siting given the significant use of the public nearshore and littoral (coastal) areas. Since 1986, leasing of nearshore areas has been legally possible, but remains fraught with difficulties. For example, site selection and orienting prospective investors is difficult as there is no single, unified database that can be examined or queried for these purposes. Even more problematic are the nearshore areas, as the ability to legally utilize them still lacks clarity and site selection is more difficult because of competing coastal uses, compared to off-shore aquaculture. Hawai‘i, as one of the few tropical areas of the U.S., stands to capture offshore investment as it offers large tracts of undeveloped coast line along with advantages offered by the U.S. legal system as compared to foreign nations where investment is still often risky. Development of a GIS database and tools which facilitate characterization of aquaculture sites based on technical, social, and legal implications would be the first step in allowing for identification of appropriate sites. In Hawai‘i, even though the aquaculture industry has roots in cultural traditions, development of a large-scale open ocean industry has been a controversial issue [19]. The collective choice rights of community members’ involvement in the process are an intangible part of the debate, although what is commonly touted and emphasized by external interests are the environmental effects [19]. Successful suitability assessments depend on how the activities and interactions of the relevant interest groups are included in the analysis, and that the decision rules are constructed in a way that all of the stakeholders’ land use criteria are satisfied.

With increasing attention focused on Hawai‘i Island’s potential for open-ocean aquaculture, the objective of this study was to develop an interactive, user-friendly database to identify potential areas for nearshore marine aquaculture that can be used by a range of management, industry, and community representatives. We expected that this interactive database planning process would identify key needs and gaps for the County of Hawai‘i and its partners in future research and economic development initiatives.

2. Methods

The suitability database was completed in nine iterative steps (Table 1), with each step including relevant stakeholders. In consultation with County of Hawai‘i Research and Development officials, we identified the extent and scale of our modeling. State boundaries extend from the upper reaches of the waves on shore seaward three nautical miles [20], the County of Hawai‘i does not have any jurisdiction over this area, but does conduct permitting and zoning on adjacent land-based activities. Since waters outside state zone are considered Federal jurisdiction (the federal Exclusive Economic Zone), we limited the scope of our project to State waters, three nautical miles offshore. No zoning designations exist for locations seaward of the shoreline. After multiple conversations between County officials, and aquaculture development experts, a 100 ha matrix of hexagons were overlaid from the shore seaward resulting in the creation of 4504 unique cells. Each 100 ha hexagon included unique attributes for that given geographic location, creating a spatial extent where modeling took place.

Hexagons have been shown to create a standard for integration of shoreline, discrete points and habitat scale information [21] and a 100 ha size was deemed the appropriate resolution for modeling.

Table 1. Stages of model development. Procedures and personnel used to identify potential sites for nearshore aquaculture.

Stage	Procedure	Source
1	Define extent, scale of nearshore area	Managers at the County of Hawai‘i, Research and Development office [1]. Aquaculture experts [2].
2	Creation of a marine aquaculture reference database	Literature search using keywords: aquaculture, mariculture, intertidal/subtidal, fishponds, cage culture, nearshore, modeling and multiple search engines
3	Define potential aquaculture systems	Aquaculture experts [2] on Island
4	Define biophysical limitations of each system	Aquaculture experts [2] on Island and Literature Search
5	Gather appropriate supporting data	GIS technicians & Oceanography experts [3]
6	Analyze scale, extent, and accuracy of data	GIS technicians & Oceanography experts [3]
7	Develop and run models	GIS technicians [3]
8	Analysis of results	Aquaculture experts, industry, and community members
9	Publication of results	Model results and supporting layers of information

Stakeholders: [1] CoH; Research and Development—Margarita Hopkins. [2] Aquaculture experts—Maria Haws PhD, Sea Grant Extension Agent; Kevin Hopkins PhD, Director of PACRC; Peter Rappa, Sea Grant Extension Agent; Neil Sims, Kona Kampachi; Syd Kraul, Pacific Planktonics; Jan War, Director of Operations NELHA. [3] GIS technicians and Oceanography experts—Noelani Puniwai, UH Hilo; Lisa Canale, UH Hilo; Kohei Miyagi, UH Hilo; Barbara Gibson PhD, UH Manoa; James Potemra PhD, UH Manoa.

2.1. Aquaculture Systems

Appropriate aquaculture systems for nearshore waters of Hawai‘i Island were identified as: (1) line culture; (2) intertidal/subtidal bottom culture; and (3) moored, caged culture by the experts and methodology described in Table 1. Cage culture is present in one location in Hawai‘i and demonstration of line and intertidal/subtidal bottom culture exist throughout the tropical Pacific. A multi-sector focus in contrast to individual cultured species allowed us to model the potential of aquaculture without limiting ourselves to known species in production. Stage 3 in the model development consisted of a series of workshops where the literature was used to inform the identification of variables of interest (Table 2).

The modeling team considered the potential to understand species or systems requirements and concluded that the largest limitation would be placed on the biophysical requirements of the technology and system, not on the biological requirements of a particular species. Biophysical system requirements, such as water quality, water quantity, and climate, were considered as well as socio-economic characteristics, such as administrative regulations, competing resource uses, and infrastructure support [14]. Finally, social values were included as public resistance and support for new ventures have resulted in limiting current aquaculture development [19,22]. A comparative case study of mariculture in Hawai‘i revealed that a large measure of public concerns focused on collective choice rights (who has a right to make which decisions on behalf of whom) and the more intangible impacts to the social or cultural environment (*i.e.*, [23]). Parameters that were considered possibly

unfeasible for operations and/or permitting, but not an outright constraint, were included in a Cautionary Layer (Table 3). The bounding criteria noted with each of these parameters were researched and indexed to individual aquaculture system types as identified in the literature. This information was crucial in the creation of the model parameters, in understanding the scale of each dataset, and the subsequent ability to use the parameter in a specific model.

Table 2. Biophysical and socio-economic constraints to aquaculture development.

Biophysical Constraints		**Socio-Economic Constraints**		
Biological	**Physical**	**Regulatory**	**Accessibility**	**Cultural Use**
Salinity	Tidal	Marine Protected Areas	Distance to Harbor	Recreational Use
Turbidity	Wave Height	Fishery Designated Areas	Shoreline Access	Cultural Presence
Chlorophyll	Flushing	Recreational Areas	Shore-based Facility	Viewshed
Temperature	Wind Speed	Shipping Lane Buoys		
Oxygen	Current Speed	Military Dumping Area		
Pollution	Ocean Depth			
Living Features	Ocean Slope			
	Substrate			

Table 3. List of parameters excluded or labeled as cautionary from all nearshore aquaculture models including buffer distances and total area.

Excluded Areas	**No. of Hexagons**	**Buffer (m)**	**Total Area (ha)**
Mooring and Navigational Buoys	14	100	1400
Underwater Cables	26	500	2300
Sewer Lines	2	100	2000
Lava Zone 1	28	0	2800
Marine Life Conservation Districts (No Take)	20	0	2000
Offshore Installations	10	100	1000
Cautionary Areas	**No. of Sites**		**Total Area**
County Parks	Terrestrial		506
State Parks	Terrestrial		231
Federal Parks	1		93,655
Precious Coral Locations	3		(point data, no associated area)
Dolphin Resting Areas	14		(point data, no associated area)
Fishery Managed Areas	10		22,646
Ocean Designated Recreation Areas	2		280,313,442
Hawaiian Islands Humpback Whale National Marine Sanctuary	1		38,631
Identified Recreational Sites	202		(point data, no associated area)
Fish Aggregation Devices	10		(point data, no associated area)

Line culture in Hawai‘i is the raising of aquatic organism on suspended, moored cables at depths ranging from 30 to 200 m. Common species raised in such systems include large algae, sponges, bivalves, and mollusks. Using the system parameters outlined in the literature and through technical expertise, we identified potential criteria for the deployment of line culture (Table 4). Moored cage culture occurs in similar conditions as line culture with cables mooring the suspended cages.

We modeled the potential for moored cages in nearshore waters of 30 to 200 m using the same parameters as listed for line culture with the exception of removing freshwater influence. The final system, intertidal/subtidal bottom culture, comprises of cages secured or placed on the bottom of the ocean and used for the raising of bivalves and algae. Organisms may be exposed to oxygen intermittently during tides, cannot be placed on live coral, and do not thrive in areas of low salinity.

2.2. Input Data

2.2.1. GIS Layers

The nearshore aquaculture models comprised of 82 different GIS data layers for use specific to Hawai‘i Island. Metadata accompanies the GIS and all data were projected into a common datum (NAD 83 UTM Zone 5N), and clipped to an extent three nautical miles offshore. All layers and their respective metadata are viewable on the website http://geodata.sdal.hilo.hawaii.edu/aquaculture/. Majority of layers were publically available, yet a few layers were accessed through the GIS technicians and made available on the website. Aquaculture experts, GIS technicians, and Oceanographers vetted all information for scale, extent, and accuracy of layers. Of the 82 GIS data layers collected and stored within the Geodatabase, a collective of 26 were used in direct creation of the final results. This geodatabase creation process was crucial in highlighting to industry and County officials the existence (or lack thereof) of information at appropriate spatial and temporal scales.

2.2.2. Geophysical Data

Another component of the operational GIS system included physical parameters such as ocean temperature, wind speed, and wave height. These parameters were thought to be essential input components to the GIS model, and data were reformatted spatially for compatibility with the GIS application. Several different satellite and model-derived estimates of ocean properties were used to describe the biophysical environment around the island of Hawai‘i. Specifically, we analyzed satellite estimates of ocean color (chlorophyll-A; mg/m^3) and sea surface temperature (℃), and model estimates of wind speed (kts) and direction, ocean current speed (kts) and direction, ocean tidal amplitude (m) and currents (kts), and wave height (m) and direction.

The constraint on geophysical data was data that included the domain of interest, but also had sufficient spatial (resolving necessary features) and temporal (meaningful climatologies) resolutions and extents. Ocean color was obtained from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Mission that is part of NASA’s Earth Science Enterprise and was designed to measure ocean color at a spatial resolution of 4.5 km. Data are freely available at the NASA/GSFC (http://oceancolor. gsfc.nasa.gov/). Higher-resolution data (e.g., MERIS 300 m) were not used since at the time of development no level 3 products were available. Ocean sea surface temperatures were obtained from the NOAA Geostationary Operational Environmental Satellites (GOES). The SST data for this study are from the imager, and provide about a 5.5 km resolution SST field. Monthly means were used.

While *in situ* and remote observations are preferable, there was insufficient coverage at the space and timescales required for the analysis. Instead, numerical models were used to provide estimates of

ocean currents and sea level variations (both tidal and wave driven). The Navy Layered Ocean Model (NLOM) and the Navy Coastal Ocean Model (NCOM) were used for ocean currents. For atmospheric circulation and tides, regional models run at the University of Hawai‘i were used. Finally, wave estimates were obtained from the NOAA National Center for Environmental Prediction (NCEP) operational model.

NLOM is a global-ocean model that was run daily by the US Navy. The horizontal resolution is relatively high at 3.5 km near the Hawaiian Islands, but somewhat coarse in the vertical; the upper layer represents the mean conditions in the top 100 m of the water column. As a computational trade-off, NLOM uses a layered approximation in the vertical (the assumption is that ocean, in the vertical, acts as a series of finite layers). The upper layer from NLOM is approximately 100 m thick and represents the upper ocean.

NCOM is similar to NLOM in the sense that it is run operationally (each day) and provides global output. However, NCOM differs in that it has a much higher vertical resolution and employs a fixed vertical grid (40 levels). Thus, the upper level is the top 5 m of the ocean. Again, because of computational limits, the horizontal grid is coarser (14 km).

For tides, the University of Hawai‘i (UH) runs a regional tidal model. Eight tidal harmonics are used to compute the baroclinic and barotropic tides around the Hawaiian Islands. The harmonics are based on climatological mean stratification (temperature and salinity) and are computed at several depths. The resulting velocity and surface elevation are computed on an hourly interval at the surface, subsurface and bottom.

Similarly, UH runs a regional atmospheric model based on the fifth-generation NCAR/Penn State Mesoscale Model (MM5), with output generated daily and archived. The model has different grids for each island, with the Hawai‘i Island grid being 1.5 km. The MM5 model was used for both wind speed and direction and precipitation estimates. In the case of winds, daytime means were constructed from the model hourly output.

The final model results to be utilized came from the NOAA/NCEP operational wave model, which is based on Wave Watch III, with and hourly results archived at the NCEP data center. The model is necessarily coarse to accommodate the high frequency needed for wave forecasting. Output is available at approximately 125 km. The result is that the entire Island of Hawai‘i shoreline is represented by four model grid points. Nonetheless, the output provides useful information about the large-scale, off-shore wave field, particularly in a climatological sense.

2.2.3. Data Layer Selection

A total of 109 hexagons (128,000 ha) from within the three nautical mile boundary were excluded as part of the final selected sites because of the presence of one of six cautionary parameters (Table 3). These parameters were chosen based on their incompatibility with aquaculture, additional permanent structures, or because of legal limitations. A cautionary layer does not exclude site selection from the model but is available for users to understand pertinent information regarding socio-economically important sites which may influence their desire to develop aquaculture initiatives. These include such variables as public recreation sites and marine managed areas.

2.3. Modeling

2.3.1. Scale and Extent of Data

Analysis of aquaculture system requirements and spatially explicit data led us to combine datasets to be able to simplify the attribution of the hexagons dataset. Values for the bathymetry came from two sources, a fine-scaled, but spatially patchy, multi-beam dataset and a modeled bathymetry recording 20 and 200 m contour lines. A combination of these datasets was used to designate the mean depth of each hexagon (m). Presence of coral substrate and heavy freshwater influence were also identified. Distance traveled to a potential aquaculture development site is limited by personnel access time required. A one hour boat ride was determined as the furthest an operator would envision to travel from shore to aquaculture site. Larger boats could use harbors and reach 25 nm in this time while smaller boats could access sites from a boat ramp and travel about 10 nautical miles within an hour (Figure 1).

Satellite imagery and modeling datasets went through extensive processing to create relevant data layers to be used in the systems modeling. Wave height satellite information was at an inappropriate spatial scale and ocean current speed models do not have accurate data nearshore that could represent ocean conditions in the locales of interest. However, wind speed was determined to be a good proxy for surface roughness. Through expert interviews, the limitations of wind speed were determined. Wind speed was queried to calculate the number of days a $\geq$ 15 knot wind blew over a surface patch for 4 h straight during daylight hours. The chlorophyll-A dataset went through similar analysis, reviewing monthly means (based on a 4 year average) to identify the time with the least concentration of chlorophyll A (October) and the number of weeks that chlorophyll A is below a minimum of 0.05 mg/m^3.

Spatial correlations were used to attribute data from the appropriate GIS data layer into the hexagon shapefile for each aquaculture system modeled. Unique identification values can therefore be queried by location for specific variables and to view the results of the models. The models for each aquaculture system were based on a simple query to identify the criteria for pertinent variables (Table 4). Additional columns were also included to reflect the results of the models. Finally, viewshed models from numerous locations were run using Esri® ArcGIS 9.3.1 applications to understand the social impact on community's seascape.

2.3.2. Stakeholder Input

Results of the models were shared at three community meetings (September 2010) and multiple informal public presentations in fall 2010 and spring 2011. Two public meetings were held in areas identified through the models as having high potential for future aquaculture development, Waimea and Kawaihae. During the meetings, construction and availability of the GIS maps were discussed, including discussion of each coastal dimension modeled and model results. The third meeting was an invitational meeting for employees of the County Economic Development held in Hilo, Hawai‘i. These focus group meeting were useful in understanding the actual benefit and applicability of the modeling exercise and comments were included in reports prepared to the County. Field notes from each of these structured and informal discussions were transcribed for analysis.

3. Results

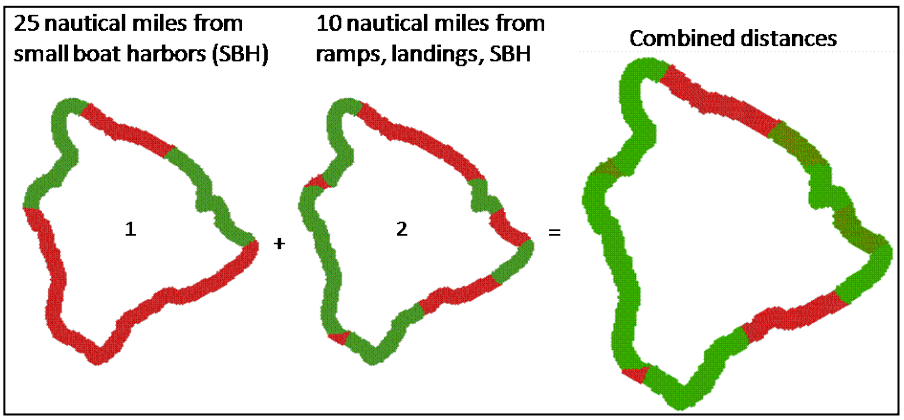
3.1. Applicability of Datasets

Analysis of all accessible datasets and their availability statewide resulted in the use or combination of nine variables in the model development. The majority of data layers were used in the socio-economic cautionary (8) or excluded (9) data layers but little data were available to identify pertinent biophysical characteristics. The majority of biophysical oceanographic information had data modeled or sampled at incompatible scales. The number of days the site would be inaccessible by boat, due to sea roughness, ranged from 0–135 days. Aquaculture sites need to be visited, maintained, or fed at least four times/week. The results show that two of every three days, a site would be accessible by boat and wind speed would not be a limiting factor in any of the models. Chlorophyll A data analysis shows that the abundance is always above the minimum threshold to provide food and nutrients to shellfish and other filter feeders. Shared parameters to all models included depth and bottom substrate, distance and accessibility for boats, nutrient availability and water quality (Table 4). Accessibility by boat was seen to be a limitation (Figure 1) in identifying potential aquaculture sites, as was appropriate reef-free shallow water habitat, and available depth habitat.

Table 4. Parameters used in the final models and associated scale (temporal and spatial).

Variables	Resolution	Criteria		
		Intertidal	**Moored Cage**	**Line Culture**
Depth	Various	4–30 m	20–200 m	20–200 m
Biological Habitat		No Coral Presence	No Coral Presence	No Coral Presence
Distance to Site	m	25 nm from harbor, 10 nm from ramp	25 nm from harbor, 10 nm from ramp	25 nm from harbor, 10 nm from ramp
Salinity	Line and Point data	No Perennial Streams or known SGD	not applicable	No Perennial Streams or known SGD
Wave Height	250 × 250 km	not applicable	not applicable	not applicable
Wind Speed	1.5 × 1.5 km Hourly means			
Chlorophyll-A	5.5 × 5.5 km Monthly means	not applicable	not applicable	Weeks Chl-A less than 0.05 mg/m^3

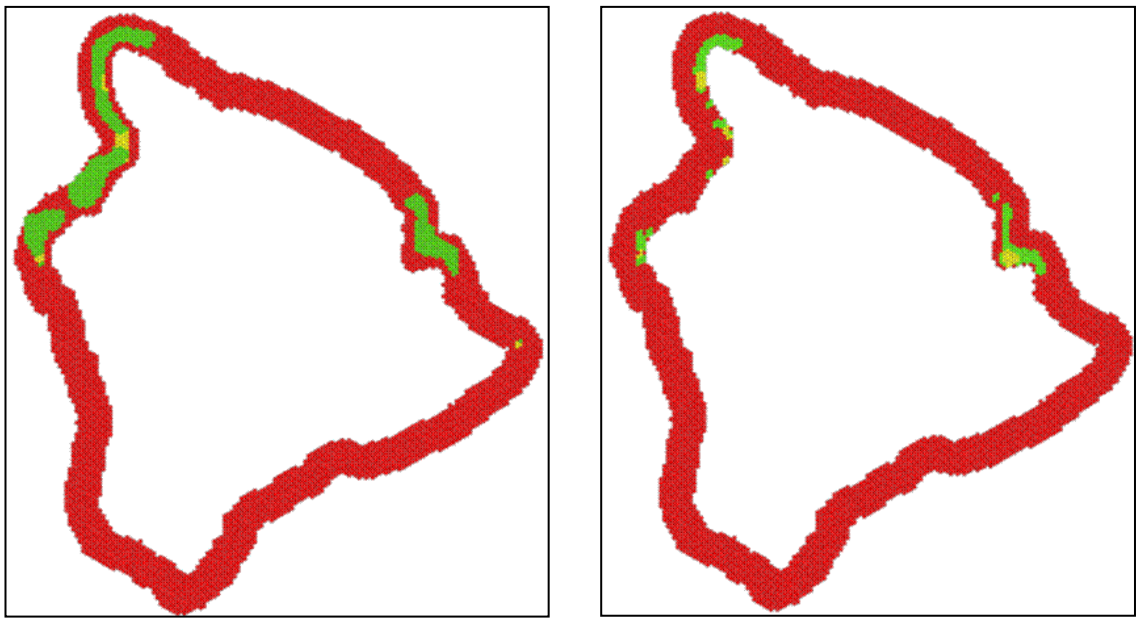
Figure 1. Accessibility of possible nearshore aquaculture sites by boats. Green areas depict sites accessible by boat and red are inaccessible based on the distance travelled.



3.2. Models

Line culture models identified 5180 ha (518 hexagons) as having potential for aquaculture development (Figure 2a). Thirty hexagons were not selected because they had a direct conflict with the obstruction layer (Figure 2). Even with the removal of freshwater impacted sites in the moored cage models, the results of the two models were the same (Figure 2a). Areas highlighted to support moored cage aquaculture in North Kona and South Kohala currently house one functioning cage and a tuna farm has been proposed. The potential to support intertidal/subtidal bottom culture was identified in 1750 ha (Figure 2b). Only 13% and 4% of areas were identified with the appropriate depth within the spatial scale of hexagons we used in the analysis for the development of line and moored cage or intertidal bottom culture, respectively.

Figure 2. Suitability of sites for line culture, moored cages, and intertidal/subtidal bottom culture. Green hexagons identify areas suited for marine aquaculture, yellow hexagons include cautionary areas, and red hexagons are unsuitable. (**a**) 5180 ha are suitable for Line Culture and Moored Cages; (**b**) 1750 ha are suitable for Intertidal/subtidal Bottom Culture.

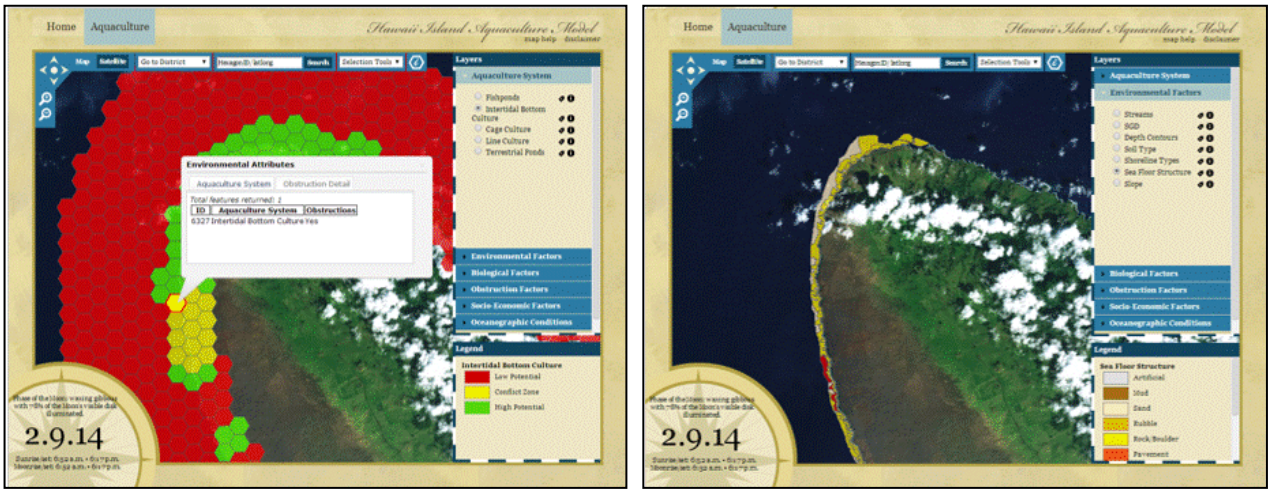


(**a**) (**b**)

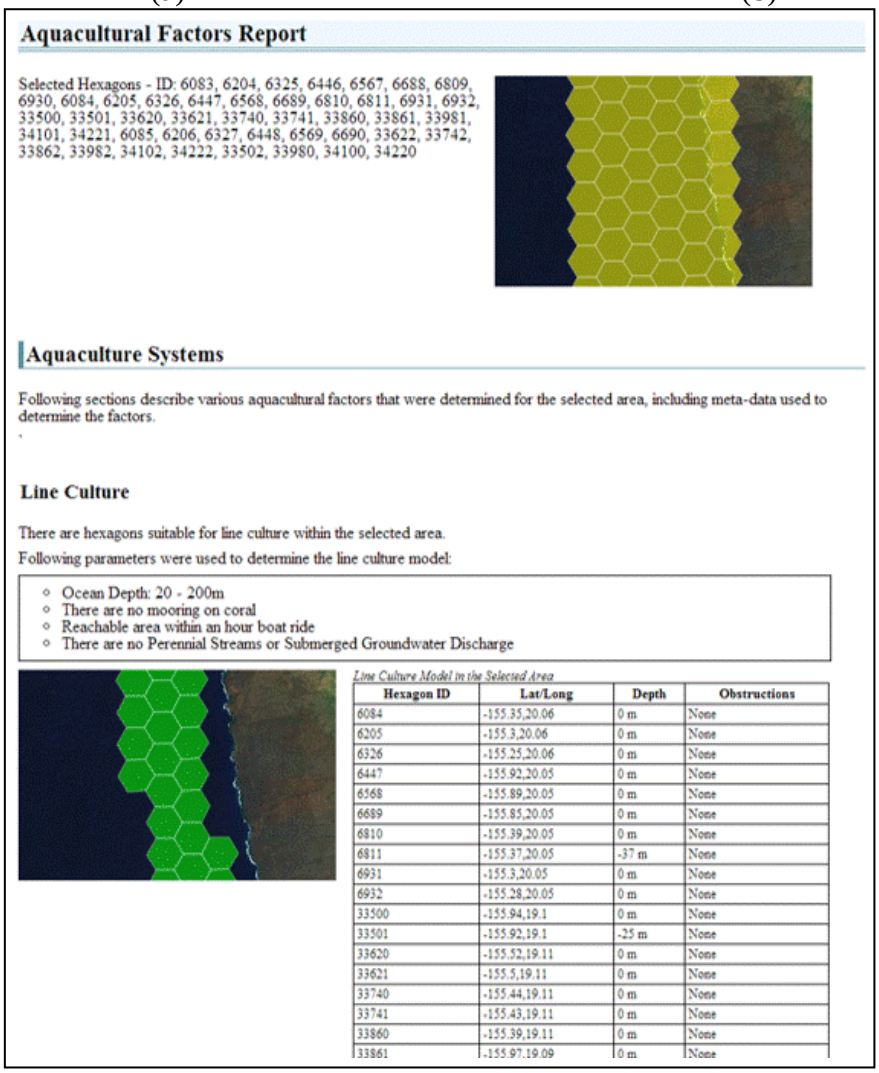
3.3. Web Interface

A considerable effort was taken to publish the modeling and GIS data sources on a public internet ArcGIS mapping site http://geodata.sdal.hilo.hawaii.edu/aquaculture/. The results of each model developed are available as individual shapefile layers, and access to each of the individual GIS layers compiled. The website allows spatial queries, the overlay of various layers, and a report function that outputs a summary of selected hexagons. The models and available data are available to the public, industry representatives, and government agencies for scrutiny and adoptability as needed. The resulting sites and background information can be used in understanding aquaculture in the context of marine spatial planning as well as for other coastal or marine management objectives.

Figure 3. Sample screen shots from the web interface. (**a**) Summary of attributes for selected hexagons with legend and layer options visible on the right; (**b**) Sample aquaculture factors report, pg.1 of 14 summarizing selected hexagon attributes; (**c**) Selection of one feature layer, sea floor structure with legend and layer options visible on the right.



(**a**) (**b**)



Aquacultural Factors Report

Selected Hexagons - ID: 6083, 6204, 6325, 6446, 6567, 6688, 6809, 6930, 6084, 6205, 6326, 6447, 6568, 6689, 6810, 6811, 6931, 6932, 33500, 33501, 33620, 33621, 33740, 33741, 33860, 33861, 33981, 34101, 34221, 6085, 6206, 6327, 6448, 6569, 6690, 33622, 33742, 33862, 33982, 34102, 34222, 33502, 33980, 34100, 34220

Aquaculture Systems

Following sections describe various aquacultural factors that were determined for the selected area, including meta-data used to determine the factors.

Line Culture

There are hexagons suitable for line culture within the selected area.

Following parameters were used to determine the line culture model:

- Ocean Depth: 20 - 200m
- There are no mooring on coral
- Reachable area within an hour boat ride
- There are no Perennial Streams or Submerged Groundwater Discharge

Line Culture Model in the Selected Area

Hexagon ID	Lat/Long	Depth	Obstructions
6084	-155.35,20.06	0 m	None
6205	-155.3,20.06	0 m	None
6326	-155.25,20.06	0 m	None
6447	-155.92,20.05	0 m	None
6568	-155.89,20.05	0 m	None
6689	-155.85,20.05	0 m	None
6810	-155.39,20.05	0 m	None
6811	-155.37,20.05	-37 m	None
6931	-155.3,20.05	0 m	None
6932	-155.28,20.05	0 m	None
33500	-155.94,19.1	0 m	None
33501	-155.92,19.1	-25 m	None
33620	-155.52,19.11	0 m	None
33621	-155.5,19.11	0 m	None
33740	-155.44,19.11	0 m	None
33741	-155.43,19.11	0 m	None
33860	-155.39,19.11	0 m	None
33861	-155.97,19.09	0 m	None

(**c**)

3.4. Stakeholder Response

3.4.1. State, Federal and Industry Response

Industry and agency stakeholders were easily engaged since they regarded the result as a functional product and had invested in the process. The models presented at the conclusion were based on their individual feedback and reflected what they had intuitively forecasted. Environmental assessments are required by state and federal laws for permitting and applications of new ventures and most of the available information that a company would require to complete these assessments were provided in the GIS maps thus saving both government and industry officials' time and financial investment. The analysis enabled agency officials to systematically service potential businesses and inform the public of the implications for future aquaculture development in their communities. Aquaculture industry participants also responded that the availability of the results on an external server increased the benefits of these public resources on data products accessible to many (Figure 3).

3.4.2. Community Responses

Two well-attended community meetings were held in locations most affected by the growing pressure for aquaculture development, and consequently, areas identified in our research as primary locations for all three types of systems; Waimea, located centrally on Hawai‘i Island and Kawaihae, located on the northwest coast. Participation from the community at the meetings varied from technical agency members to aquaculture supporters and skeptics, with over 75 individuals participating. Community members received the modeling attempt and result with mixed reactions. Having the result accessible through an ArcGIS website allows community access to information and knowledge that are normally technically too advanced for them to acquire. The model results allowed community members to know that as aquaculture pressures grow, they could use the web tool to query, understand and present information on their behalf. This accessibility was an unintended result that served not only the aquaculture industry but also the communities faced with development on their local coastal areas. Critical feedback was shared in relation to the coarseness of the model results. Community members are interested in areas at much finer scales than the models showed, and in aquaculture systems that were irrelevant to these nearshore models, such as inland fishponds and salt beds.

4. Discussion

The overarching results highlight nearshore aquacultures need for large areas with shallow depths, and access from nearby harbors and boat ramps. Hawai‘i's waters were also shown to have great potential to host future aquaculture development, especially with increased development along the South Kohala, North Kona coastline. Of the multitude of GIS data layers publicly available, 24 were not available at the appropriate spatial and/or temporal scale but likely would have contributed significantly to the results of the modeling exercise. Even with more robust spatial data, the limiting factors for developing off-shore aquaculture are likely to be depth and availability of prime habitat. If biophysical factors were available at finer scales, they may have also been a limiting factor. However,

we were unable to integrate them as presented. The final results were useful for county/industry representatives but the data products have failed thus far to be useful for community decision-making.

The County of Hawai‘i, with little GIS expertise, gained a valuable tool in assisting planning, and development. Though industry and agency experts deemed this project resourceful and useful, comment from individual community members and response from public presentations highlighted the limitations by exemplifying the inability of our data products to serve the needs of all stakeholders. Particularly, we were unable to: (1) identify data products at the scale most pertinent to use both temporally and spatially; and (2) modify the scale of the model to reflect levels of development universally applied to varying economic scales of operations.

4.1. Temporal and Spatial Scales

We were unable to use 24 GIS layers, including incomplete bathymetry and benthic habitat maps, location of underwater obstructions, socio-economic variables, and oceanic conditions as measured by satellites. As can be expected, many of these data are a priority for management agencies and their availability has improved over time. Importantly for this modeling exercise, however, is that most biophysical oceanographic parameters have spatial resolutions that are not applicable for coastal applications. Many ocean satellite data and ocean models have outputs at very fine temporal scales (hourly, daily, weekly) but at large spatial scales (5.5 km^2, 14 km^2) and thus their resolution along the coastline when projected was inaccurate (e.g., some satellite imagery overlain on the terrestrial landscape). As satellite and remote sensing technology continues to increase in resolution, models will be able to incorporate these new datasets. Although we were able to query and transform the wind speed and ocean color datasets, understanding the pertinent temporal and spatial scales in which to use the data was dependent on industry experts.

4.2. Economic Scales of Operation

As with any geographic analysis, data resolution (e.g., pixel size) matters. Specifically, using smaller hexagons may have identified additional areas suitable for aquaculture at a smaller scale of development. Hence, our scale of analyses inadvertently was skewed towards support of industrial scale aquaculture and not small scale growers. This skew particularly affected the modeling results of intertidal bottom culture. Hawai‘i Island has very limited shallow areas and by using a hexagon grid size of 100 ha, shallow areas that did not extend through a majority of a hexagon were determined too deep while concurrently, areas too close to the shoreline were identified as terrestrial. Using hexagons of scalable size may increase the amount of potential sites identified for intertidal bottom culture and should be considered for future research.

4.3. Community Involvement

Approaching this exercise with the knowledge that aquaculture development is a contentious yet feasible area of current and future development there was a guided effort in involving stakeholders ranging from industry experts to community groups throughout the process. Planning increasingly involves non-experts (public, communities, and stakeholders) in the planning and decision making

process and this evolution have been paralleled by the increasing accessibility (user-friendliness) of GIS technology [24]. Presenting the process and the results in a non-biased approach from a research group not tied to the results was received neutrally as hoped. Many projects such as these are completed by interest groups tied to either development or anti-aquaculture perspectives and residents are hard-pressed to be educated with an open approach. Ball [25] states that participation by stakeholders in the process of the planning phase ensures cooperation by local inhabitants in the final plan and as a vehicle to gain access to local knowledge, complementing scientific knowledge.

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Author Contributions

Conception and design of the study: Maria Haws, Noelani Puniwai. Collection, analysis and interpretation of data: Noelani Puniwai, Lisa Canale, James Potemra. Drafting of the article: Noelani Puniwai, James Potemra. Critical revision of the article for important intellectual content: Noelani Puniwai, James Potemra, Christopher Lepczyk, Steven Gray. All authors read and approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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