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GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan

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ABSTRACT

Production from Japanese scallop (*Mizuhopecten yessoensis*) aquaculture is increasing, and supports coastal communities. To ensure both success and long-term sustainability of providing scallop productions, finding suitable sites is an important step in any aquaculture operation. This study was conducted to identify the most suitable sites for hanging culture of Japanese scallop using geographic information system (GIS)-based multi-criteria evaluation models. Remote sensing data (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Land Observing Satellite (ALOS)) were used to extract most of the parameters. Seven thematic layers were grouped into two basic requisite for scallop aquaculture, namely biophysical (sea temperature, chlorophyll, suspended sediment and bathymetry) and social–infrastructural (distance to town, pier and land-based facilities). A constraint layer was used to exclude the areas from suitability maps that cannot be allowed to develop scallop aquaculture, including harbor, area near town/industrial and river mouth. A series of GIS models was developed to identify the most suitable areas for scallop culture using multi-criteria evaluation known as weighted linear combination. Suitability scores were ranked on a scale from 1 (least suitable) to 8 (most suitable), and about 56% of the total potential area with bottom depths less than 60 m had the higher scores (scores 7 and 8). These areas were shown to have the optimum condition for scallop culture in this region. The final suitability model outputs were compared with field verification data and found to be consistent.

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1. Introduction

Production from Japanese scallop (*Mizuhopecten yessoensis*) aquaculture is increasing, and supports coastal communities. This industry plays an important role in the economic and social welfare of the coastal communities and has grown to become the most successful marine shellfish farming venture in Japan (Shumway, 1991; Bourne, 2000); currently, over 40% of the scallop production in Japan is from aquaculture (FAO, 2007). The main cultivation areas are located in the north of Honshu Island and on Hokkaido Island. According to the Ministry of Agriculture, Forestry and Fisheries (2005), Hokkaido contributed almost 80% of the scallop production in Japan during 1991–2002; the main culture areas in Hokkaido are the Sea of Okhotsk, Saroma Lake and Funka Bay. In this areas, the main culture methods used are a combination of bottom seedling and suspension (hanging) culture techniques.

Despite the rapid growth, aquaculture development continues to be hindered by a number of constraints. These include limited suitable

sites, concerns regarding impacts on the environment, and multi-use conflicts. Improper aquaculture development may result in over-exploitation and un-sustainability on the use of natural resources. To prevent such problems, stock enhancement has been practiced in harmony with the environment and is clearly reflected in the increased production (Uki, 2006). On the other hand, finding suitable sites for aquaculture is an important step in any aquaculture operation, affecting its success and sustainable development. Appropriate location of aquaculture development will minimize the risk of environmental impact, maximize the overall economic return and minimize conflict between aquaculture and other resource uses (GESAMP, 2001). Aquaculture has to be incorporate into the coastal management plans and needs to reduce negative impacts on other resources users in the same location whilst also earning the respect of other users in regard to its own development (Stead et al., 2002). Site suitability analysis may form the basis for control and management of aquaculture development. Those analysis that can be built according to specific criteria, includes environment characteristics (physical, biological and ecological factors), social economics and support facilities.

Resources use and development has explicit spatial dimensions. To make development sustainable, it is necessary to develop an analytical framework that can incorporate spatial (and temporal) dimensions of

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parameters that effect sustainability (Frankic, 2003). Geographic information system (GIS) and remote sensing have a role to play in all geographic and spatial aspects of the development and management of aquaculture. Both GIS and remote sensing technology are also used to define geographic framework, specify environmental constraints and identify resource limitations (Stead et al., 2002). In common applications, remote sensing has become an important source of data used in GIS analysis. Using this technology can reduce the amount of field sampling and increases the spatial and temporal coverage of estimation. Parallel with these developments, GIS has greatly enhanced our ability to store, analyze and communicate this information. The central element of a GIS is the use of a location referencing system so that data about a specific location as well as its attributes can be compared to other locations (Burrough and McDonnell, 1998). The capabilities of evolving GIS and remote sensing provide a powerful tool for the efficient and cost effective management of sustainable aquaculture. This technology is also useful for facilitating the decision making process for coastal planners in relation to aquaculture. The use of GIS and remote sensing in planning for aquaculture development, together with selected cases have been documented (e.g., Meaden and Kapetsky, 1991; Nath et al., 2000; Kapetsky and Anguilar-Manjarrez, 2007). The applications of GIS in site selection for various different aquaculture industries have been reported such as hard clam culture in Florida (Arnold et al., 2000), scallop culture in Sungo Bay, China (Bacher et al., 2003), shrimp and crab farming in Bangladesh (Salam et al., 2003), marine fish cage culture in Tenerife, Canary Islands (Pérez et al., 2005) and mangrove oyster raft culture in Margarita Island, Venezuela (Buitrago et al., 2005).

Funka Bay is an important area for scallop aquaculture development. Scallop culture is economically important to coastal communities around the bay. The scallop cultivation area in this bay has increased about 1.6 times from 1982 (12% cultivation area) to 2003 (19% cultivation area) (Miyazono, 2006). However, with the rapid development of scallop culture, concepts such as carrying capacity and ecology footprint need to be considered in relation to sustainability aquaculture activities. Many studies have been carried out in Funka Bay, and most of them emphasized environmental characteristics (e.g.,

Ohtani and Kido, 1980; Kudo and Matsunaga, 1999; Sasaki et al., 2005; Takahashi et al., 2005; Radiarta and Saitoh, 2008) and the influence of environmental factors on biota under culture (e.g., Kurata et al., 1996; Shimada et al., 2000). This paper presents a GIS-based multi-criteria evaluation (MCE) that uses remotely sensed data and field verification data to identify the most suitable sites for hanging culture of Japanese scallop development in Funka Bay.

2. Materials and methods

2.1. Study area

Funka Bay is a semi enclosed bay in southwest Hokkaido (Fig. 1). The longitudinal axis of the bay is aligned northwest–southeast. It lies between 42°00′–42°35′ North and 140°18′–141°00′ East, with a mean and maximum depth of 38 m and 107 m, respectively. The bay has a 2315 km² surface area, and a 195 km coastline, and is connected to the northwest Pacific Ocean through a 30 km wide shallow sill in the east part of the bay.

As it is a semi enclosed bay, physical and biological conditions govern the marine environment in the bay. Water in the bay is replaced twice a year by the inflow of Tsuguru warm water from autumn to winter and Oyashio water (a subarctic oceanic water mass) from spring to summer (Ohtani, 1971; Ohtani and Kido, 1980). Each replacement time takes about 2 months (Miyake et al., 1988). Sea surface temperature in the bay varies from <5 °C in March to >20 °C in August–September (Shimada et al., 2000). Salinity is relatively stable, ranging from 31 to 34 psu. Chlorophyll-*a* levels are very high during the spring bloom in March, but relatively low (<1 µg l⁻¹) during summer (Shimada et al., 2000; Odate and Imai, 2003). Wind conditions vary seasonally; winds are southeasterly in summer and northwesterly in winter (Inoue et al., 2000). Funka Bay is also influenced by terrestrial materials, such as from river discharge, and urban and industrial effluents (Sasaki et al., 2005). Most riverine discharge comes from the Yurappu River located in Yakumo, along with some smaller rivers between Noboribetsu and Shikabe.

Funka Bay has favorable environmental conditions for aquaculture and is one of the most important aquaculture areas in Hokkaido.

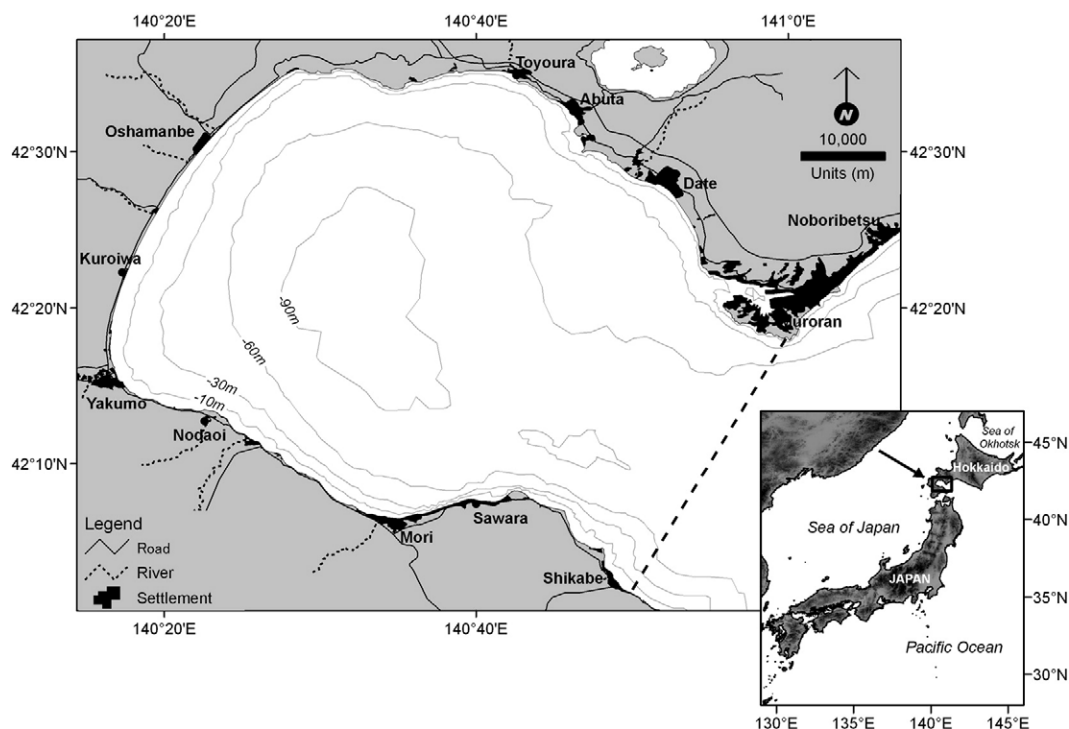


Fig. 1. The study area, Funka Bay, southwestern Hokkaido, Japan and major depth contours. Dashed bold line indicates border of the study area.

Scallop and kelp are also widely cultivated by individuals, companies and fishermen associations.

2.2. Software and hardware used

The remote sensing and GIS software used in this study were SeaDAS 4.9 (GSFC/NASA, USA), ERDAS Imagine 9.1 (ERDAS Atlanta, GA, USA) and ArcGIS 9.2 (The Environmental System Research Institute, USA). Data processing and modeling were performed mainly with ArcGIS 9.2, while SeaDAS 4.9 and ERDAS Imagine 9.1 were used for satellite image processing. ArcGIS 9.2 was operated on a Pentium Celeron 2.80 GHz workstation with a 1 GB RAM, 160 GB harddisk. The display was a DELL 17 in. color monitor.

2.3. Identification of criteria and data collections

Although many factors have to be considered for developing scallop aquaculture (Hardy, 1991; Kingzet et al., 2002), the most important depends on the culture system utilized by the farmers. The influence of sea temperature, food availability (measured as chlorophyll-*a*), suspended sediment and bathymetry on the growth of bivalves has been well documented, especially for scallops (e.g., MacDonald and Thompson, 1985; Bacher et al., 2003) and mussel (e.g., Hatcher et al., 1994; Ellis et al., 2002). In addition, social and infrastructural factors also affect operations (Nath et al., 2000; Kingzet et al., 2002). So, these parameters were used for identifying suitable sites for scallop culture in Funka Bay (Table 1).

The primary data sources used included multi-sensor remotely sensed data (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Land Observing Satellite (ALOS)), a hydrographic chart and global positioning system (GPS) data. Sea surface temperature data were derived from the MODIS-Aqua sensor as level-2 data with 1 km resolution from the Distribution Active Archive Centre Goddard Space Flight Centre National Aeronautic and Space Administration (DAAC/GSFC/NASA) (Savtchenko et al., 2004). A total of 287 images with good coverage were collected from June 2002 to August 2004. All images were combined to generate a composite map, which was used to generate average values of sea temperature. Then this image was reclassified according to suitability scores.

Daily level 2 of SeaWiFS data with 1 km resolution from February 1998 to August 2004 were obtained from DAAC/GSFC/NASA (Acker et al., 2002). Each data file contained derived chlorophyll-*a* and the six water leaving radiances (nL_w , see http://oceancolor.gsfc.nasa.gov/PRODUCTS/SW_nlw.html). The chlorophyll-*a* images were processed using the SeaWiFS chlorophyll algorithm Ocean Color 4 version 4 (OC4v4) (O'Reilly et al., 1998). A total of 307 images with good coverage were selected. All images were combined to generate a composite map, which was used to generate average values of chlorophyll-*a*. Then this image was reclassified according to suitability scores.

From the daily SeaWiFS data that were downloaded (described in the previous paragraph), nL_w (555) data were extracted. Monthly averages of nL_w (555) images were used to calculate suspended sediment (SS) images ($g\ m^{-3}$) following Ahn's equation (Ahn et al., 2001):

$$SS = 3.18 * nL_w(555)^{0.95}$$

where nL_w (555) is normalized water leaving radiance at 555 nm. All images were combined to generate a composite map, which was used to generate average values of suspended sediment. Then this image was reclassified according to suitability scores.

A hydrographic chart from the survey map of the Japan Hydrographic Department (1:150,000) was scanned on a Canon (CanoScan FB620U) scanner with 200 dpi resolution, edited in Adobe Photoshop version 5.5 (a raster format image-editing software), and imported into GIS software. The image was digitized using on-screen digitizing to produce bathymetric features (point data). The Triangulated Irregular Network (TIN) technique was used to create a complete bathymetric map, either as raster data or vector data (contour map). Then this map was reclassified according to suitability scores.

Social-infrastructural and constraint data were extracted from ALOS Advance Visible and Near Infrared Radiometer (AVNIR)-2 image with 10 m resolution, acquired on August 12, 2007. The image was downloaded from the AUIG website (ALOS User Interface Gateway, <https://auig.eoc.jaxa.jp/auigs/en/top/index.html>) as level 1B2G (geo-coded). On-screen digitizing was the technique chosen to produce social-infrastructural features as well as constraint data (Table 1). The final step was to run distance analysis (using ArcGIS spatial analyst) to measure distances from the each data (social-infrastructural and constraint) and reclassify them according to suitability scores.

Since multi-sensors were used, the geo-reference of these images into a uniform spatial reference is required to accurately overlay the spatial database in the analysis. Thus, the coastline of the study area, which was obtained from The International Steering Committee for Global Mapping (<http://www.iscgm.org/cgi-bin/fswiki/wiki.cgi>) was used as a base map to which all images were geo-referenced. In all cases, some control points were required, and the root mean square was kept under one pixel length. All spatial data used in the GIS models were built on a WGS 84 UTM zone 54 North coordinate system. Data on the above parameters prepared for input to the GIS database were built based on 10×10 m pixels size (Ross et al., 1993; Pérez et al., 2005).

2.4. Database generation and weighting procedure

The model structure for identifying suitable sites for scallop aquaculture in Funka Bay was built based on hierarchical structures (sometimes referred to as a value structure). Hierarchical structures break down all criteria into smaller groups (or submodels). At highest levels are the most general objective which can be further define at

Table 1
Criteria used for Japanese scallop aquaculture site selection in Funka Bay, southwestern Hokkaido

Submodel	Criteria	Interpretation of criteria	Data sources (resolution)
Biophysical	Sea temperature	Favorable temperature for scallop culture	MODIS-Aqua (1 km)
	Chlorophyll- <i>a</i>	Availability of natural food (phytoplankton)	SeaWiFS (1 km)
	Suspended sediment	Indicate level of water clarity (turbidity)	SeaWiFS (1 km)
	Bathymetry	Favorable depth for hanging culture	A hydrographic chart (1:50,000)
Social– infrastructural	Distance to town	Labor sources	ALOS AVNIR-2 (10 m)
	Distance to piers	Support services	ALOS AVNIR-2 (10 m)
	Distance to land-based facilities	Support services	ALOS AVNIR-2 (10 m)
Constraint	Harbor (inside and entrance)	Pollution and navigation	ALOS AVNIR-2 (10 m)
	Town/industrial	Viewshed and pollution	ALOS AVNIR-2 (10 m)
	River mouth	Freshwater, pollution and suspended matter supply	ALOS AVNIR-2 (10 m)

still lower levels. While the lowest levels of hierarchy are attributes (Malczewski, 2000). Fig. 2 shows suitability analysis for scallop culture site selection in Funka Bay as a hierarchical structure. This study identified 11 criteria according to the basic requisite for scallop aquaculture in Funka Bay. These criteria were organized into three submodels (biophysical, social–infrastructural and constraint), represented either as factors or constraint (Nath et al., 2000). A factor is a measure of the suitability of the criterion relative to the activity under consideration. A constraint is a restriction that serves to limit the alternative under consideration, including harbor, town/industrial areas and river mouth and is Boolean format (containing either one or zero).

All data integrated into the spatial database needed some manipulation and reclassification to create a standard scoring method. Scoring of raw data was based on the requirement of the scallop culture system. A suitability score for each criterion was established according to Pérez et al. (2005) using a scoring system from 1 to 8, with 8 being the most suitable and 1 being the least suitable for developing scallop culture.

The next stage was to establish a weighting for each criterion and factor. Although a variety of weighting techniques exist (Malczewski, 1999), the pairwise comparison method developed by Saaty (1977) in the context of the analytic hierarchy process (AHP) was used to develop a set of relative weights for each parameter in MCE. Consequently, information about the relative importance of the criteria is required. At this stage, decision-maker's preferences with respect to the evaluation criteria were incorporated into the decision model. The preferences were typically defined as a value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration. Criteria were rated according to literature reviews and experts' opinions based on their relative importance using the pairwise comparison method (Table 2). By making the pairwise comparisons for each criterion and factor, we can develop relative weights, in order to account for changes in the range of variation for each criterion and different degrees of importance being attached to these ranges of variation (Malczewski, 1999). In the pairwise comparison, the relative importance of the criteria was evaluated on a 17-point continuous scale from least important (1/9, 1/8, 1/7, ..., 1/2) to most important (1, 2, 3, ..., 9) for each activity being evaluated. After comparisons were made, the principal eigenvector of the pairwise comparison matrix was computed to produce the best fit for a total weight of 1. The benefit of using AHP is its ability to calculate the consistency ratio of weight distribution and its consequent evaluation of the weighting process. This value indicates the probability that ratings were randomly assigned. A consistency ratio

Table 2

A pairwise comparison matrix for assessing relative importance of biophysical and social–infrastructural factors for Japanese scallop aquaculture site selection in Funka Bay, southwestern Hokkaido (numbers show the rating of the row factors relative to the column factor)

Biophysical	SST	Chlorophyll	Suspended sediment	Bathymetry	Weight
SST	1	4/3	2	4	0.4
Chlorophyll	3/4	1	3/2	3	0.3
Suspended sediment	1/2	2/3	1	2	0.2
Bathymetry	1/4	1/3	1/2	1	0.1
Consistency Ratio (C.R.): 0.00					
Social–infrastructural	Distance to town	Distance to piers	Distance to land-based facilities	Weight	
Distance to town	1	3/2	2	0.46	
Distance to piers	2/3	1	4/3	0.31	
Distance to land-based facilities	1/2	3/4	1	0.23	
Consistency Ratio (C.R.): 0.00					

of 0.1 or less was considered acceptable and demonstrated good consistency in judgment (Saaty, 1977; Banai-Kashani, 1989).

2.5. Constructing the GIS model

The model of suitability site has been implemented using model builder in ArcGIS. It was constructed based on the MCE procedure known as the weighted linear combination (Malczewski, 2000), in which the weight of the relative importance assigned to each criterion and a total score, $V(x_i)$, is then obtained for each criterion by multiplying the weight assigned by the scale value for that criteria, and summing the product over all parameters as follows:

$$V(x_i) = \sum_j w_j r_{ij}$$

where w_j is a normalized weight, such that $\sum w_j = 1$, and r_{ij} is the attribute transformed into the comparable scale. The weights represent the relative importance of the attributes. The most preferred alternative is selected by identifying the maximum value of $V(x_i)$ for $i = 1, 2, \dots, m$.

The final suitability map was created by combining two different models. These models were calculated using the different relative importance weight scenarios for biophysical and social–infrastructural submodels (Table 3). The general purpose of this analysis was to find out the influence of different criteria weights on the spatial pattern of the suitable site. The relative importance weight scenarios were assigned according to the situation not only present at the moment but also in the long run. Then it is possible to change the weights of different preference criteria. For each scenario, a different decision factor is given the greatest importance: biophysical > social–infrastructural set as model 1 and social–infrastructural > biophysical

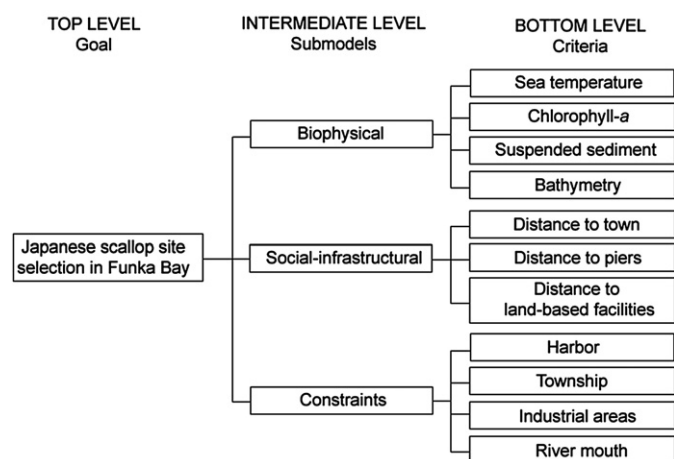


Fig. 2. A hierarchical modeling scheme to identify suitable site for Japanese scallop aquaculture in Funka Bay, southwestern Hokkaido.

Table 3

A pairwise comparison matrix for assessing relative importance of final site selection models for Japanese scallop aquaculture site selection in Funka Bay, southwestern Hokkaido (numbers show the rating of the row factors relative to the column factor)

Factor requirement for assessment of scallop culture site selection	Biophysical	Social–infrastructural	Weight
Model 1 (biophysical > social–infrastructural)			
Biophysical	1	3/2	0.6
Social–infrastructural	2/3	1	0.4
Consistency Ratio (C.R.): 0.00			
Model 2 (social–infrastructural > biophysical)			
Biophysical	1	2/3	0.4
Social–infrastructural	3/2	1	0.6
Consistency Ratio (C.R.): 0.00			

Table 4
Different suitability levels (expressed as percentage of the total potential area) for Japanese scallop aquaculture site selection in Funka Bay, southwestern Hokkaido

Factors/criteria	Suitability scores (%)								
	0	1	2	3	4	5	6	7	8
<i>Biophysical</i>									
Sea temperature	0.0	0.0	0.0	0.0	0.1	0.4	1.0	26.8	71.7
Chlorophyll	0.0	11.0	0.1	0.2	1.0	5.0	23.0	27.7	32.0
Suspended sediment	0.0	2.0	2.0	3.0	2.0	3.0	4.0	17.0	67.0
Bathymetry	0.0	7.0	2.0	4.0	3.0	4.0	2.0	3.0	75.0
Sub-overall	12.0	0.0	0.0	0.1	3.0	3.3	3.2	36.0	42.4
<i>Social–infrastructural</i>									
Distance to town	0.0	8.0	3.0	5.0	7.0	10.0	12.0	14.0	41.0
Distance to pier	0.0	13.0	6.0	7.0	5.0	5.0	6.0	7.0	51.0
Distance to land facility	0.0	15.0	3.0	3.0	4.0	5.0	5.0	6.0	59.0
Sub-overall	12.0	11.0	6.0	4.0	6.0	8.0	6.0	9.0	38.0
Overall model 1	12.0	0.0	0.0	0.0	0.0	16.0	20.0	29.0	23.0
Overall model 2	12.0	0.0	0.0	10.0	6.0	6.0	17.0	19.0	30.0
Overall suitability of site	12.0	0.0	0.0	0.0	10.0	8.0	14.0	20.0	36.0

Total potential area is 1038 km², using only area with depth less than 60 m.

set as model 2. This analysis is useful in situations such as where uncertainties exist in the definition of the importance of different factors (submodel). In many cases, it is important also to know how the results will change if the weights change (Siddiqui et al., 1996; Malczewski, 1999).

2.6. Verification

Model verification is absolutely essential, both for quality control of certain data and for testing the outcomes of the models (Nath et al., 2000). Model verification was carried out by making comparisons between the suitable-sites model and existing scallop aquaculture operations. The global positioning system (GPS) data of existing scallop aquaculture produced by a local fisheries experimental station was mapped and overlaid with the suitability sites model to determine how much the existing scallop culture matched with the suitable sites.

3. Results

3.1. Areal distribution of submodels

Sites with water depth between 15 and 30 m are ideal for hanging culture, which will allow for tidal fluctuations. It is essential that the media of culture should not be in contact with the seabed to prevent

predators such as starfish and crabs from feeding on the scallops. In our models, to focus on the areas of maximum interest for development of scallop culture using hanging technique, we selected 60 m as the maximum depth in order to minimize operation costs and difficulty in mooring system.

Although suitability maps of each parameter were made for the whole bay (about 2315 km²), the area distribution of suitability scores for each criteria was calculated only for areas where the water depth is less than 60 m (potential area about 1038 km²). The result for seven criteria (as factors) and constraint layer is presented separately in two submodels, namely biophysical and social–infrastructural, enabling comprehensive analysis. The classifications of surface areas for each criterion are summarized in Table 4, and the corresponding spatial distributions of suitability sites are shown in Fig. 3.

The potential sites should have appropriate biophysical variations including both biological habitat and physical environmental parameters in order to provide the optimum condition for growth and survival of biota under culture. In our model, sea temperature, chlorophyll, suspended sediment and bathymetry were the criteria used to examine biophysical characteristics. Approximately two-fifth of the potential area (42%) was identified as score 8 (most suitable), and this area was located in the southwestern and northeastern part of the region (Fig. 3a). No area had a score of 1 or 2. Approximately 67–75% of potential area had score 8 (most suitable) for scallop culture in terms of sea temperature, suspended sediment and bathymetry (Table 4). While chlorophyll-*a* was accounted for 32% for the score of 8.

Social–infrastructural can be used as a tool to directly improve productivity and product quality. Social–infrastructural factors (distance to town, piers and land-based facilities) are well supported for scallop aquaculture development in the study area (Table 4), with an easy access and well distribution of the facilities. Approximately 38% of the potential area was classified as score 8 (most suitable) for scallop culture in term of social–infrastructural factor. About 9% had a score of 7. Approximately 20% and 10% of potential area were classified as middle score (sum of scores 4, 5 and 6) and lower score (sum of scores 2 and 3), respectively. Only 11% of potential area was classified as score of 1 (least suitable) which is located mostly far away from social–infrastructural facilities (Fig. 3b).

The constraint layer limits the suitability site for scallop culture. Harbor area (inside and entrance) located in Muroran, areas near the river mouth (e.g., Yurappu river in Yakumo and other small rivers) and areas near the township and industrial (Fig. 1) were considered as constraint (score 0). They covered about 12% of the potential area in our model (Table 4).

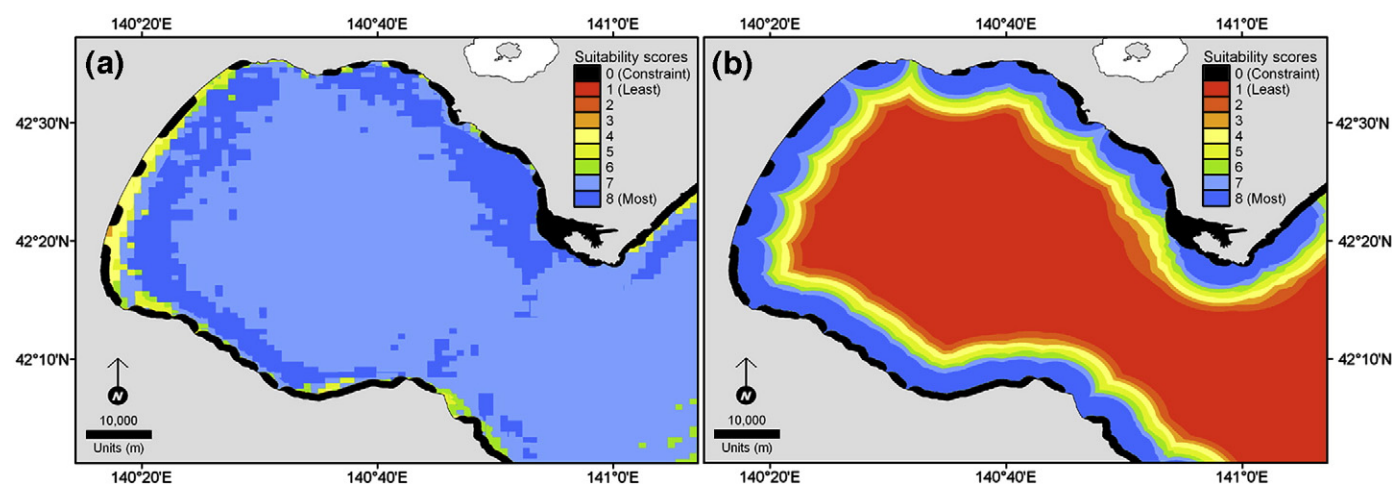


Fig. 3. Suitability maps of different submodels generated for Japanese scallop aquaculture in Funka Bay, southwestern Hokkaido. (a) Biophysical submodel and (b) social–infrastructural submodel.

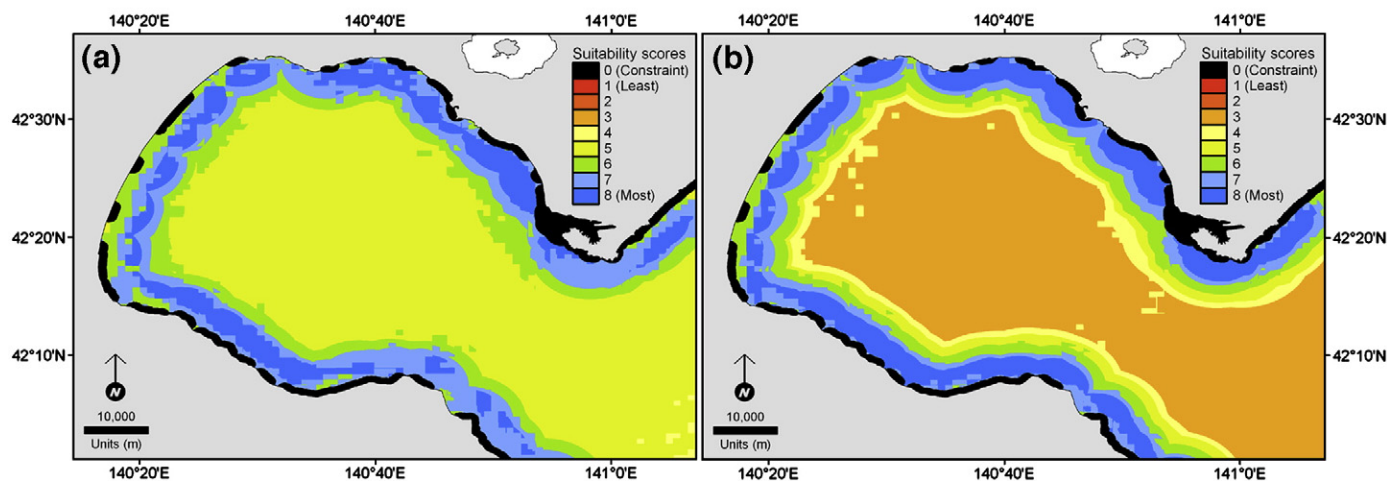


Fig. 4. Suitability maps of different scenario models generated for Japanese scallop aquaculture in Funka Bay, southwestern Hokkaido. (a) Model 1 (biophysical > social-infrastructural) and (b) model 2 (social-infrastructural > biophysical).

Different relative importance weight scenarios were applied for two submodels (biophysical and social-infrastructural), enabling the sensitivity analysis to be taken into consideration in the process of producing the suitability area. On the other hand, to investigate how changing the weight of various factors affected the determination of the preferred area. The different suitability levels for each model scenario are presented in Table 4, and the corresponding spatial distributions of suitability sites are shown in Fig. 4. In model 1, biophysical is given the greatest relative importance (Fig. 4a). About 23% of the area was identified as score of 8 (most suitable), while 29% had a score of 7. Approximately 36% of the potential area had scores 5 and 6. There was no area identified as lower scores (scores 1, 2, 3 and 4). Whereas, when social-infrastructural is given the greatest relative importance (Fig. 4b), about 30% of the area was identified as score 8. Most suitable area (score 8) has increased compare to model 1. This is mainly due to easy accessibility and well-established social-infrastructural facilities in this region. Only 19% of the area had score 7. However, 29% and 10% of the area were ranked as middle score (sum of scores 4, 5

and 6) and lower score (score 3) suitability. No area was identified as scores 1 and 2.

In the final output for scallop culture site suitability (Table 4 and Fig. 5) where the bottom depth is less than 60 m (potential area about 1038 km²), the model classified about 36% of this potential area had a score of 8 (most suitable). This area appeared like a belt along the coastline from Shikabe to Muroran that has ideal conditions for the criteria examined. About 20% had a score of 7, while 32% of the area was ranked as middle score (sum of scores 4, 5 and 6). However, there was no area identified as lower scores (scores 1, 2 and 3).

3.2. Verification of the model

Verification was done by comparing the location of existing scallop culture operation and suitability of location obtained from the models. The results are shown in Table 5. It is important to note that some areas (1%) that have already been developed for scallop culture were located in the constraint model output. These are situated at

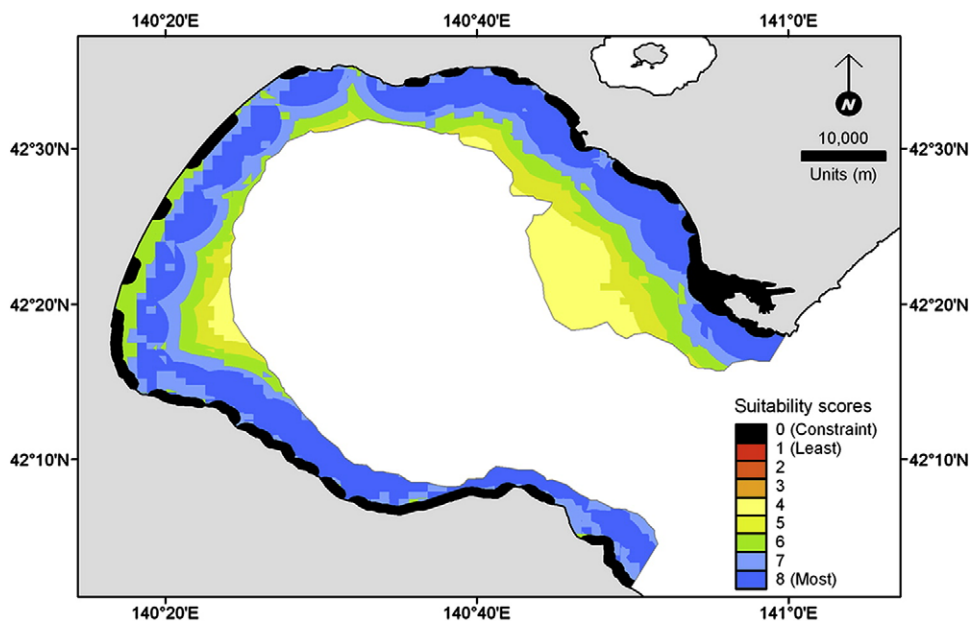


Fig. 5. Overall site selection map, masked to depth of exceeded 60 m, for Japanese scallop aquaculture potential in Funka Bay, southwestern Hokkaido.

Table 5

Model verification (expressed as percentage of the total potential area) between existing scallop aquaculture operations and suitability scores obtained from the models in Funka Bay, southwestern Hokkaido

Scallop aquaculture	Suitability scores									Total
	0	1	2	3	4	5	6	7	8	
Available	1.0	0.0	0.0	0.0	0.0	0.0	1.0	8.0	25.0	35.0
Not available	11.0	0.0	0.0	0.0	10.0	8.0	13.0	12.0	11.0	65.0
Total	12.0	0.0	0.0	0.0	10.0	8.0	14.0	20.0	36.0	100.0

Total potential area is 1038 km², using only area with depth less than 60 m.

northeastern region of the study area including Muroran, Abuta and Toyoura. In these areas, scallops are mostly cultured near to harbor or settlement.

Twenty-five percent of most suitable (score 8) and 9% of suitable (scores 6 and 7) model output were matched with existing scallop aquaculture location. No existing scallop aquaculture locations were found below score 6 (Table 5). Even though most of the most suitable model output (score 8) have been utilized for scallop culture location, still about 11% of most suitable model output available which were located outside of the existing scallop culture location.

4. Discussion

This study focused on the selection of the most suitable sites for hanging culture of Japanese scallop. Different criteria were grouped into two submodels, namely biophysical and social–infrastructural, which were combined to generate a final output showing the most suitable sites for scallop aquaculture development in Funka Bay. Although, the total potential area in this study is 1038 km² (area with water depth less than 60 m), only about 88% (913 km²) could be classified as suitable for scallop, while the remaining 12% (125 km²) was identified as constraint areas (include harbor, area near the township, industrial and river mouth). Classification of suitability level using GIS techniques led to estimates that 56% and 32% of the potential area had high score (scores 7 and 8) and middle score (scores 4, 5 and 6), respectively, for the scallop culture development. Areas with the highest scores were evenly located around the coastal area from Shikabe to Muroran (Fig. 5). The most suitable (highest scores) areas for scallop culture are those in which most of variables coincide with each other and there is high potential for scallop production. The results of this GIS models are validated by the existing scallop culture operation locations in the study area (Table 5). Existing scallop culture covers about 69% of area classified as most suitable (score 8) in the study area. This indicates that further expansion of scallop culture to other areas is possible. However, this study is based only on site selection for scallop culture. Other important factors such as potential users of coastal area (i.e., tourism, coastal recreation, conservation and fishing operation) should also be considered in order to integrate all the potential uses under the coastal zone management scheme. In some case, management option will be required when certain activities appear in the same location based on suitability analysis of the area. In this situation, the choice has to be based on environmental requirements for the activity, as an example Pérez et al. (2003a) analyzed the potential area for development of marine fish cages in terms of their coexistence with the tourism industry in the Canary Islands.

Determining parameter weights is a crucial phase in the analysis. A slight change in weight coefficients can have a significant effect on the results of the suitability analysis. To include the effect of sensitivity weight, we combined two difference relative importance weights in order to achieve the final output. Two scenarios are presented here to demonstrate the effect of relative importance weight selection on suitability ranking. The areas of each suitability levels revealed slight changes when the weight is emphasized on one factor either

biophysical or social–infrastructural (Table 4; Fig. 4). Siddiqui et al. (1996) have also demonstrated difference scenarios weight when they analyzed site suitability for landfill in Cleveland County, Oklahoma.

This study showed the usefulness of the GIS database of different formats and sources can be used effectively to identify spatial model of suitability levels for scallop culture. Salam et al. (2005) pointed out two factors that can improve the site selection analysis such as adding more specific criteria and using the site specific data for the criteria under consideration. On the other hand, the quality and quantity of information available (i.e., up to date and high quality data) to decision making can make precise estimation (Nath et al., 2000). In this study most of the data used were extracted from satellite data (SeaWiFS, MODIS and ALOS AVNIR-2). Satellite data assimilated into GIS and integrated with other databases can provide rich information system, which is more sophisticated and useful in substantial applications. These technologies represent a major step towards facilitating decision making and optimizing coastal uses (Stead et al., 2002). The use of satellite data for planning and managing aquaculture activities has been emphasized by many studies (e.g., Kapetsky et al., 1987; Meaden and Kapetsky, 1991; Rajitha et al., 2007). Recently, satellite ocean color data gains much attention by many researchers to be used in aquaculture studies (IOCCG, 2000). Chlorophyll concentration, suspended sediment and sea surface temperature (SST) are typical data that can be extracted from satellite ocean color and are being used in aquaculture researches. However, the use of satellite data in this study might be possible sources of inaccuracy. The satellite data measurements reflected surface values and not represent the bulk values (at depths where hanging culture might be holding the majority of the scallop stocks). Most successful uses of satellite data concentrate on identifying spatial gradients rather than absolute values. These data have provided an enormous leap in our ability to view the spatial and temporal variations. SST data has been used by Pérez et al. (2003b) for analyzing marine fish cage culture site selection in Tenerife (Canary Islands), and showed appropriate results. On the other hand, with the availability of ALOS satellite which is dedicated for the global high resolution earth observation (Igarashi, 2001), it is possible to extract land cover/land use which is being the major use in aquaculture planning and management.

Scallop aquaculture is one of the priorities for development and promotion of aquaculture activities in Japan (Yamamoto and Hayase, 2006), because this species is cultured without food supply and its growth based on the availability of natural food (mainly phytoplankton). Scallop culture has indicated less impact on environment (Crawford et al., 2003). However, to enhance and maintain scallop productions, aspect of carrying capacity needs to be considered (McKindsey et al., 2006; Miyazono, 2006). On the other hand, distance between farms should be maintained to avoid a negative effect especially where disease is a problem. Also some space is required for other activities such as navigation. The distances between farms vary greatly between countries depending on environment characteristic, systems used and regulations or guidelines. As an example, minimum distances between shellfish farms in South Australia are at least 1 km and 100 m for subtidal and intertidal site, respectively (Anonymous, 2000). To enhance production of aquaculture and to avoid or lessen an impact on environment, an integrated seafarming based on multi-species aquaculture or 'polyculture' is one possible solution (Shumway et al., 2003; Yamamoto and Hayase, 2006). A commercial marine polyculture in which two or more species are produced may greatly improve output because of the beneficial interaction between species. Polyculture farming system has been demonstrated to be a viable option by many studies such as shellfish and salmon (Parsons et al., 2002) and shellfish and seaweed (Yang et al., 2005). The integration of shellfish and seaweed can avoid pronounced shifts in coastal process, so that the wastes from one resource user become a resource for the others (Stead et al., 2002). This culture technique might be applicable in Funka Bay, because scallop and kelp are intensively cultured in this

area. Kelp grown on raft with scallop forms an integrated culture system which greatly improves growth and yield of both species (Scoggan et al., 1989). However, improvement of the models to define the appropriate proportions between different co-cultured organisms (e.g., kelp and scallop) requires more research and development.

Site selection analysis in this study could a benefit from data improvements. It might be well that other environmental parameters remarkably influence scallop growth and survival, and recognize as important in estimating the capability of a site to sustain the productions, such as dissolved oxygen, salinity, pH, wave height, water movement (tidal flow), fouling/disease/predators, pollution (or sewage) and seed availability (Nath et al., 2000; Kingzet et al., 2002).

This study demonstrated the use of GIS to model site selection for scallop culture in Funka Bay based on a certain important criteria and showed acceptable results. GIS is a particularly useful tool for facilitating the decision making process for coastal planners in relation to aquaculture in order to optimize use of natural resources. The advantage of GIS is the ability to update, integrate and analyze to generate new ratings easily when new (up to date and high quality) data becomes available. Nath et al. (2000) described in detail about GIS technology and methodology for formulating GIS-based aquaculture project and include some case studies. On the other hand, implementation of final decision must incorporate socio-economic and cultural factors which will allow coastal planner to make better decisions. Stead et al. (2002) pointed out that management of coastal resources including mariculture has little consideration given to the view of stakeholders. Therefore, involving many stakeholders (communities) in planning and decision making process is an important step toward acceptability and success of the sustainability management of scallop culture in this region.

5. Conclusions

The application of the developed GIS model shows that it works effectively to establish spatial models for identifying the most suitable areas for hanging culture of Japanese scallop development. As expected, most of the areas at the bay had high suitability scores. This is because, most of the parameters (biophysical and social-infrastructure) in the study area are favorable for scallop culture development. This study shows that with appropriate information (i.e., remote sensing), GIS used in modeling is a powerful tool for site selection decision making. As more data become available either from satellite images or field measurements, the usefulness of this tool will increase and provide a range of functions embedded in various components that can be tailored for optimum site selection.

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