On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands)

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Abstract

The lack of suitable sheltered sites is forcing fish farmers to move to more exposed offshore locations in order to provide for continued growth in the industry. However, as farmers move to more exposed sites for ongrowing, extreme weather conditions must be regarded as a normal environmental condition. For appropriate cage system selection and siting sufficient wave data has to be available, as wave action (wave climate) on floating cage structures may create conditions where failures are likely. At present, there are many methods of estimating wave climate, but none has been clearly presented for its use in offshore cage culture siting, particularly in a format that may be used within an integrated selection tool. This paper presents a novel methodology for wave climate characterisation in offshore fish cage site selection, based on a case study for sitting offshore seabass and seabream cages in Tenerife (Canary Islands). The mid-term statistic was used to identify prevailing wave heights and the long-term statistic or extreme wave analysis was used to identify the likely highest waves over a certain time period (15 years). The former can promote gradual failure of structures, while the latter may cause instant total failure. Based on this information, three cage systems were selected and, a suitability map was created for each using Geographical information systems, showing the more suitable zones to site the cages.

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Keywords: Waves; Cage culture; Aquaculture; Site selection; Tenerife; GIS

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1. Introduction

Selection of a suitable site for an aquaculture venture determines investment, running cost and strongly influences the ultimate success of the resulting aquaculture enterprise (Lawson, 1995). Particularly in the case of cage culture, most fish farm sites have been placed in relatively sheltered waters but there are a finite number of such suitable sites. A variety of pressures are now ensuring that the future of mariculture is likely to be further offshore, with the whole trend of the industry being towards larger units, supporting deeper and heavier nets in more exposed waters. In addition, the industry is subjected to lobbies by other water users, regulatory authorities and environmental agencies. Mariculture is also facing increasing numbers of objections from those in the tourist industry who regard fish farms as an offensive intrusion upon the best natural vistas, and the increase and rapid transmission of endemic diseases to adjoining areas has resulted in a general movement of production to farther offshore. Moreover, it seems clear that inshore sites with restricted depths and water transfer are leading to the need to fallow sites on a regular basis, with associated increases in cost of production. Sheltered sites might even affect the quality and health of the fish themselves (Beveridge, 1996) as dispersal of waste products from cages on such sites is less effective thereby incurring the risk of local pollution (Fearn, 1990). More exposed sites, offshore, would overcome many of these problems.

Offshore mariculture has other advantages. It has been reported that profits are slightly higher in offshore cages than inshore (Myrseth, 1991). However, despite these advantages opinions seem heavily divided on the long-term feasibility of offshore designs. The proponents of offshore aquaculture point out that mounting pressures coupled with continually rising world demand for food, and declining wild stocks of fish make the move offshore inevitable, whereas detractors insist there is not enough profit to drive the capital investment required for offshore farming, particularly as investors and underwriters have already had the burden of huge losses in conventional aquaculture, and may therefore be reluctant to support it in even more extreme conditions (Turner, 1991).

Of all the possible environmental problems in offshore cage culture, wave action is of most concern. Knowledge of the wave action at a potential site (also called wave climate) will help the choice of a proper cage and mooring technology for the site, as well as estimating the risk of failure (Cairns and Linfoot, 1990). Both likely highest waves over a certain period (design wave or return wave) and prevailing or average wave heights are significant measures in assessing the cage system structure. The former may cause instant total failure, while the latter will promote gradual failure or what is commonly know as ‘structural fatigue’. This is important for calculating the frequency of replacement of different parts of the cage structure. In addition, greater wave motion increases relative motion between water and nets suspended from a slow-moving collar, which has implications for the ability of staff to operate in rough weather. Higher relative motion not only requires much stronger net enclosures, but also may cause de-scaling of the fish during storms, with consequent osmotic trauma, increased disease risks and mortalities (Turner, 1991).
The challenges of siting and operating cage systems in exposed sites fall into two major areas; storm survival and servicing or operating capabilities. Neither area has a substantive track record of experience on which to base decisions (Willinsky and Huguenin, 1996). At present, there are diverse methods of estimating wave climate, but none has been clearly presented for its use in offshore cage culture site selection. This paper tries to fill that gap by presenting a simple but accurate methodology, the practicability of which is tested by presenting a case study for siting fish cages in Tenerife (Canary Islands). For the design of coastal and offshore structures it is important to predict the combined effect of the extreme wave height and associated wave period (Liu and Wang, 1986). Nevertheless, this paper focuses solely on wave height estimations as this is a more general and straightforward indicator for siting cages. The use of wave periods, although an important variable, is more dependent on the cage design, mooring structure, cage orientation, etc. (Whittaker et al., 1990), and so it was not included.

2. Methodology

2.1. Wave statistic

Wave statistics can be classified into three main categories according to their time scales; short-term, mid-term and long-term. The short-term statistic or significant height, \( H_s \), is the average height of the one-third highest values in a continuous series. Goda (1977) found that this was the most stable parameter to characterise ocean waves which are subject to statistical variability due to irregularity of wave profile. The simplest medium-term statistics are monthly, seasonal or annual averages of sea state (wave condition described by means of height, period and direction parameters). They are particularly useful in describing wave conditions at a specific locality. The usual way of presenting and analysing this type of data is by mean of plots and histograms, which may provide a first indication of trends, if any, and visual comparison between months or years. Another mid-term statistic often analysed is the marginal distribution of wave height in the form of non-exceedance, which is the probability that a wave height \( (H_i) \) is smaller than a fixed critical value \( (H_c) \). This calculation is needed for the use of the long-term statistic.

For design of coastal structures it is very important to obtain information on wave characteristics over a period of time sufficiently long to cover the lifetime of the structure. Normally, these measurements are either unavailable or scarce. One way to solve this problem is to represent wave statistics using a probability function which fits the data, and then to obtain the necessary design information from that probability function. Ordinal statistics, which deal with data dispersion around a population mean, are of little value as it is necessary to know the distribution far away from the mean. Study of a phenomenon in its extreme conditions requires the use of statistical methods specifically designed for it.

The reliable estimation of extreme waves is normally based upon the data for the significant wave height, \( H_s \), which is then fitted to one or more probability
distributions. This gives the cumulative probability distribution function, \( P(H_s) \), for different \( H_s \) values. It should be kept firmly in mind that there is no physical, theoretical or empirical reason for preferring one distribution to another (Muir and El-Shaarawi, 1986). The approach commonly used is to try several candidate distributions with each data set and select the one that fits best. The fitted distribution is then extrapolated to obtain the design \( H_s \) value corresponding to a known magnitude of \( P(H_s) \) that in turn it is derived from a specified return period. The return period is defined as the average time interval between successive events of an extreme significant wave height being equalled or exceeded. The main problems involved in calculating extreme wave heights are to obtain sufficiently accurate wave data, and to employ proper statistical techniques in the calculations.

Possible wave data sources are marine buoys, use of records of visual height observations and modelled data. Numerical simulation of wave transformation processes is an extremely rational and efficient method of quantifying wave behaviour (Wei et al., 1990). Two different methods are currently employed to prepare extreme statistics of storm waves. The Total Sample Method, employs the whole wave data record at regular intervals of a few hours, whereas the Peak Value Method (PVM), uses the wave heights from individual storms to construct an extreme wave data set. The data set for the PVM can be either a partial-duration series (used in this study) or the annual maximum series. The reliability of predicted extremes is directly related to the accuracy of available data and the number of years recorded. As a general rule-of-thumb, heights can be extrapolated to return periods up to three times the length of record (Borgman and Resio, 1977).

The extreme wave calculation methodology used in this study is basically that proposed by Goda (1979), Goda and Asce (1988) and Muir and El-Shaarawi (1986), in which an input array of extreme significant wave heights are fitted to five candidate probability distributions. The candidate distribution functions are Fisher-Tippett Type I and Weibull with exponents ranging from 0.75 to 2.0. Goodness-of-fit information is used to identify the distributions which matches best with the input data. General assumptions in this approach are: (1) all extreme wave heights come from a single statistical population of storm events, (2) wave height properties for an event are reasonably represented by the significant height, (3) extreme wave heights are not limited by any physical factors such as shallow-water depth, (4) the data must be independent of each other, (5) probability distributions must be constant from storm to storm, (6) the probability distribution \( P(H_s) \) is not only constant, but also its functional form is known except for the constants, and (7) data must be stationary and all autocorrelation has been removed.

2.2. Geographical information systems

In recent years Geographical information systems (GIS) have become widely used in environmental planning and assessment, principally because of the need to compare a great number of spatially-related data describing the affected natural resources. GIS has several advantages for aquaculture development programs. It not only provides a visual inventory of the physical, biological and economical
characteristics of the environment, but its modelling capability allows generation of suitability map layers for different uses or activities without complex and time-consuming manipulations. GIS technology has been used in aquaculture for about 15 years. A wide range of studies targeting different species (fishes, shrimps, mussels, oysters and clams) at different scales (local, regional, national and continental) has shown the general usefulness of the methodology (Aguilar-Manjarrez and Ross, 1995). Nath et al. (2000) and Welcome (2001) present an extensive review on the applications of GIS in aquaculture, while Ross et al. (1993) show an example based on salmonid cage culture.

2.3. Hardware and software

The GIS software IDRISI 32.11 and the spatial data builder software CARTALINX 1.2, were operated on a twin 400 MHz PII PC with 512 MB RAM and 45 GB harddisk. Display was via a DELL 21 colour monitor. Some digitising was done using a CalComp Drawingboard III table. ACES (Automated Coastal Engineering System) 1.07f software was used for the long-term statistic calculations.

3. Tenerife case study

3.1. Study area

The aim of this study was to select the most suitable sites for offshore marine fish-cage farming of seabream (Sparus aurata) and seabass (Dicentrarchus labrax) based on available technology and practices, in Tenerife (Canary Islands). The Canary Archipelago, composed of seven main islands and several minor ones, is located in the Northeast Atlantic Ocean between latitude 27.6°−29.5° N and longitude 18.2°−14.5° W, only 100 km from the northwestern edge of the African continent (Fig. 1). The archipelago emerged from the oceanic basin due to the successive overlay of volcanic material, forming an independent set of islands with a water depth of 2000 m between them. Tenerife is the largest island, having a surface area of 2.036 km² and a coastline of 358 km. It has a triangle-based pyramid shape with a truncated apex at an altitude of 2000 m, from which the volcano Teide rises to 3.718 m. Its volcanic nature is responsible for the coast and seabed topography, which can be generally described as abrupt and rich in unevenness. The insular shelf is reduced to only 200 m.

3.2. Data

Data screening identified four possible sources of wave data for the study area; visual observations from ships, six land-based wind stations (which could be used to estimate wave heights; US Army Corps of Engineers, 1984), two marine buoys and 15 WANA points (which are the daily wave forecast output from the fourth generation WAve Model, WAM (Günther et al., 1991), used by the Spanish
Department of Maritime Climate). The WAM-model solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. It represents the physics of wave evolution in accordance with our current knowledge for the full set of degrees of freedom of a 2D wave spectrum. Visual observations from ships and wind data (Fig. 2) were not used due to their inaccuracy relative to the other available data sources and also their lack of coverage. Similarly, although marine buoys are the most accurate source of information, the limited spatial coverage afforded by only two buoys (Fig. 2) did not provide enough detail for this study. Therefore, the 15 WANA points were used as the data source as their coverage (Fig. 2) and predicted accuracy (Fanjul et al., 1998) is adequate for this study. The WANA data was provided by The Spanish Department of Maritime Climate. The wave records used cover a period of 5 years with a temporal resolution of 6 h, from 1995 to 1999, with 6740 values of $H_s$, $T_p$ and mean wave direction per

Fig. 1. The study area, Tenerife, Canary Islands.
WANA point. The image used for Tenerife island in this study is a $10 \times 10$ m pixel image provided by CD-Map (1999).

3.3. Calculating and mapping the mid-term statistic

Mid-term statistics were used to characterise the average wave regime in Tenerife (the mean wave height over the full data set). The data was individually analysed for each of the 15 WANA points. To provide a first indication of possible data trends, Fig. 3 shows the mean $H_s$ and the standard deviation, while Fig. 4 shows the maximum $H_s$ for each point.

The average wave energy for each location is also an important parameter that provides an indication of the environmental stress that a fish cage will need to withstand. The energy of a sinusoidal wave (per unit area of wave in deep water) can be divided into potential energy ($E_p$) and kinetic energy ($E_k$), and its combined formula can be expressed as the average energy density ($E$) by following Eq. (1) (Pond and Pickard, 1983);

$$E = E_p + E_k = \frac{\rho g H^2}{8}$$  

(1)

where density of seawater, $\rho = 1.025 \times 10^3$ (kg/m$^3$); acceleration of gravity, $g = 9.807$ (m/s$^2$); wave height, $H$ (m).

Fig. 5 shows the average wave energy (J/m$^2$) and the standard deviation for the 5-year data set. A limited version of this approach was used to successfully quantify...
kelp canopy responses to several wave energy levels over a single peak storm period (Bushing, 1997).

Figs. 3–5 illustrate qualitative differences between sites, from which four groups can be identified. To test for the presence of these four groups, each with a similar wave regime, a hierarchical cluster analysis (percentage similarity association with
The unweighted paired-group method for arithmetic averaging was used (Kent and Coker, 1994). The cluster analysis produces a dendrogram (Fig. 6) which is a visual representation of a similarity association between points with similar wave characteristics. The branching pattern of the dendrogram illustrates the similarity between the various clustered objects, in that the more closely they are linked, the more similar they are.

The combined use of the dendrogram (Fig. 6), the mean and maximum $H_s$ (Figs. 3 and 4), and the average wave energy density (Fig. 5) was used to characterise the Tenerife coastline according to wave exposure. Wave characterisation identified four
major zones (Fig. 7). Points 1, 2, 3 and 4 form a very homogeneous group (zone-1), characterised by the highest wave exposure of all. These locations show the highest wave heights and the greatest average energy density. They are located in the N and NE, where there is most exposure to wave action. The second zone, composed of points 5, 12, 13, 14 and 15 may be classified as a high exposure area, characterised as having high average energy density, but smaller maximum wave heights than zone-1. This zone may be further subdivided into two sub-zones, one composed of points 5 and 12 and the second by points 13, 14 and 15. The former may also be seen as a ‘transitional zone’ between the N and S wave regimes of the island. Zones-1 and -2 are the most exposed areas of the island due to their opening to the Trade Winds coming from the NNE and the stormy weather from the N during winter and the beginning of spring.

Fig. 8 shows the mean distribution of wave direction for each WANA point in zones 1 and 2, with waves coming mostly from the N to NE, N and N to NW, respectively. Points 15 and 12 show smaller frequencies of waves coming from the N to NE owing to a more sheltered position. Point 12, which has been classified as transitional, shows slight differences and has a higher frequency of waves coming from the W to NW than others in this group. Point 5, which was also classified as transitional, is most distinctive with the majority of its waves coming from the N to NE.

The third zone, formed by points 10 and 11, is located in the SW part of the island. This zone is characterised by a medium to low wave regime throughout most of the year (Fig. 9). However, some sporadic episodes of high waves occur when stormy weather come from the SW. Looking at the total energy density, these two points can be classified as medium exposure sites. The mean wave direction distribution for
Fig. 8. Distribution of mean wave direction for WANA points 1, 2, 3, 4, 5, 12, 13, 14 and 15.

Fig. 9. Distribution of mean wave direction for WANA points 10 and 11.
these two points show that most of the waves come from the N and NNE. However, there is a small frequency of waves coming from the NNW to W. The N to NE wave frequency at point 11 is lower than at point 10 owing to shelter provided by the island.

Zone 4, points 6, 7, 8 and 9 on the S and SE, was classified as a low exposure area. The mean wave height and the energy density analysis (Figs. 3 and 5, respectively) do not show differences among the four sites. However, based on the dendrogram (Fig. 6) and values of maximum $H_s$ (Fig. 4) the group can be subdivided into two distinct sub-groups; point 6 and 7, and points 8 and 9, based on differences in highest wave heights which are higher at points 8 and 9, due to their proximity to stormy weather coming from the SW. The mean wave direction distribution for these points (Fig. 10), although apparently similar, also show some differences between the two sub-groups. The main wave direction for these four points is NE, although points 8 and 9 have a distinct NW component.

Information on the mean wave heights together with information on wave direction was used to generate the mean wave height map for Tenerife. Prevailing wave directions coming from each WANA point were extracted from the wave direction distributions (Figs. 8–10) and interpolated using Voronoi Tessellation techniques (Fig. 11).

Fig. 10. Distribution of mean wave direction for WANA points 6, 7, 8 and 9.
Fig. 11. Mean wave height exposure map for Tenerife (wave heights in metres).

Fig. 12. Extreme wave height exposure map for Tenerife (wave heights in metres).
### 3.4. Calculating and mapping the long-term statistic

The monthly maximum wave values of extreme significant wave height for each of the 15 WANA points were analysed using ACES version 1.07f software. From the five distribution functions fitted to each WANA point that with the highest correlation and smallest sum of the square of residuals was chosen as the probability distribution which best fits with the data set. Table 1 shows the significant wave height for a 15-year return period calculated for each WANA point, their associated confidence intervals and the probability distribution selected. In this study return periods higher than 15 years may not be significant as only 5 years of data were available for calculations.

Information on the 15-year return wave heights together with information on wave direction was used to generate the extreme wave height map for Tenerife. Knowing the exact location of each WANA point and the wave direction of the 20 highest waves recorded in each point, prevailing wave directions were estimated. The extreme wave height map was created by interpolation using Voronoi Tessellation techniques (Fig. 12). This showed that the roughest conditions are mostly located on the northern and western coasts, while along the southern coast there is a regular decrease of wave height from east to west.

### 3.5. Cage selection

Selection of a suitable sea-cage design for a particular offshore location should take into account several factors (1) economic—capital cost amortisation and

<table>
<thead>
<tr>
<th>Point</th>
<th>$H_s$ (m)</th>
<th>Lower confidence interval (m)</th>
<th>Upper confidence interval (m)</th>
<th>Probability distribution selected</th>
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<td>3.90</td>
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<td>3.04</td>
<td>2.55</td>
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<td>FT-I</td>
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<tr>
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<td>9.51</td>
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routine maintenance (operating cost), (2) biological—maintenance of optimum stock holding conditions including minimisation of exposure to disease, stress and maintenance of water quality levels through adequate water exchange, and (3) engineering—structural integrity, longevity and safety (Linfoot et al., 1990). This study focussed only on the engineering aspects.

Tenerife has a broad range of wave climate as seen from Figs. 11 and 12, ranging from a mild environment on the southern and south-eastern coasts to a highly exposed environment on the north coast. Three cage systems were selected as suitable for deployment based on their ability to withstand these conditions. However, none of the cage manufacturers provide a written specification of wave heights for which the cages are considered suitable. The little available information which manufacturers offer are from computer modelling, small scale laboratory tests or empirical data from specific operating sites.

For the very dynamic sites (high exposure), rigid submersible cages which would retain their volume are suggested. Self-tensioned and self-supporting cages hold their shape in the absence of weights but will also do so without any anchor line tension. The submersible systems can avoid storm effects effectively, since wave forces decay hyperbolically with increase of water depth. Even modest submersion below the surface substantially reduces wave forces from local storms (Willinsky and Huguenin, 1996). Based on these requirements, the SeaStation® (Fig. 13a) was chosen. This cage has at its core a single spar, around which an eight sectioned rim is placed. The nets are strung between the top and bottom of the spar to the rim so that the cage resembles two cones with their bases connected together.

In the intermediate exposure sites, rigid cages (anchor tensioned) should also be used. Anchor tensioned cages rely on very taut moorings to hold their shape and volume, and they are not dependent on weights for maintenance of net shape. Any external forces applied to the netting enclosure will cause the anchor line tensions to increase which, in turn, resists cage deformation. Fish are therefore able to swim in greater net volumes throughout the whole cage. For these mid exposure sites the Ocean Spar® cage system (Fig. 13b) was chosen.

Finally, for the low energy sites, the simplest and cheaper gravity cages could be used. Gravity cages usually consist of surface floats in the form of a circle or polygon, from which a net enclosure is hung. The term ‘gravity cage’ derives from

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Fig. 13. The three cage systems chosen, (a) SeaStation®, (b) Ocean Spar® and (c) Corelsa® (redrawn, with permission, from Loverich and Gace, 1997).
the fact that the net is prevented from becoming flattened in water currents by weights hanging onto the bottom of the net enclosure. Even so, gravity cages can lose more than half their volume in the presence of strong currents (Aarsnes and Rudi, 1990). The fish in a gravity cage subjected to wave motion are normally very excited, swimming in broken schools only where the net volume is greatest, effectively reducing the net volume even further. Though there are many gravity cage systems to choose from, Corelsa® cages were selected (Fig. 13c) as this system is already being used successfully in Tenerife.

3.6. Cage siting (suitability maps)

Sea cages and the fish within them can only tolerate certain sea states. In moderate to severe wave conditions, cages positioned at the sea surface, or just below, act as breakwaters and are subject to the destructive pressure of breaking waves. Simultaneous exposure to the circular water motion beneath these surface wave fields affects moorings, flotation collars, nets, and fish stocks (Willinsky and Huguenin, 1996). Therefore, appropriate siting for each of the selected cage systems is crucial to ensure their longevity (operating life) against wave action, as well as safety for the operators.

To generate the suitability maps for siting each of the cage systems, the two wave exposure maps (Figs. 11 and 12) were reclassified (scored) and combined using a scoring system of 1–8, with 8 being most suitable and 1 least suitable. Similar studies have used standardized criterion scores of 1–4 and 1–16 (Aguilar-Manjarrez, 1996; Salam, 2000), but it was found that the former scoring system gave poor results while the latter was too complicated to use. The scores were based on interpretation of cage designs obtained from the manufacturers and literature, and are shown in Tables 2 and 3. Figs. 14 and 15 show the extreme and average wave height suitability maps, respectively, for each of the cage systems.

The wave suitability maps were finally combined into a single map to estimate the overall suitability of areas for fish farming with each cage system. When combining the maps a weighting was used to give more importance to extreme wave height, as this may cause sudden cage failure and is thus of greatest concern. The extreme wave height layer was given a weighting of 0.7 and the average wave height layer a weighting of 0.3. Fig. 16 shows the final suitability wave maps for each of the proposed cage systems.

<table>
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<th>6</th>
<th>5</th>
<th>4</th>
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<td>6–7</td>
<td>7–8</td>
<td>8–9</td>
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<td>Ocean Spar®</td>
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<td>4–5</td>
<td>5–6</td>
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<td>8–9</td>
<td>9–10</td>
<td>&gt;10</td>
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<tr>
<td>Corelsa®</td>
<td>0–3</td>
<td>3–3.5</td>
<td>3.5–4</td>
<td>4–4.5</td>
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<td>&gt;6</td>
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4. Discussion

This study presents a clear, simple and accurate methodology for wave climate characterisation for fish cage site selection, as shown in a case study in Tenerife. Three cage systems were selected and suitability maps for each of these created. The results showed that cage systems most able to withstand harsher environments would be suitable for use over a greater area of Tenerife coastline. Thus, the more robust self-tensioned cage (SeaStation®) could be used over a greater area than the weaker gravity cages (Corelsa®). However, the selection of the three cage systems used in this study was only based on their capability for withstanding certain wave climate and other factors, economic and practical, should also be considered.

Bugrova (1996) studied the economical feasibility of different cage systems, including offshore cages. He showed that capital cost is 43% higher for semi-submerged than for floating cages, however this is compensated by lower labour costs, lower feed costs, better survival rate and higher fish quality. He concluded that in ‘real terms’ the unit production costs for floating systems are 3% higher than those for semi-submerged ones. Therefore, operations that use semi-submerged and submerged cages may be most effective.

Assessing risks against benefit of the offshore aquaculture industry is likely to focus heavily on weather damage, and cage and mooring failures due to extreme weather conditions associated with offshore practices (Smith, 1990). Increased use of offshore farm sites has resulted in the requirement for accurate pre-development information about the wave climate for specific areas (Bell and Barr, 1990). Barker (1990) suggested that extreme values of environmental factors which are not exceeded once in every 100 years should be used for fish farming siting. However, in waters where the environmental data is well established, e.g. the European continental shelf, a 50-year return period may be acceptable. Other authors are less rigorous. Nayak et al. (1990) suggested that only 5–10 years wave data was necessary for reasonable prediction of a maximum design wave. It is therefore reasonable to assume that a return period which covers the lifetime of the structure (15–20 years) is satisfactory for siting an offshore cage system, although, of course, longer data periods are always desired and recommended.

Table 3
Scoring system for reclassification of the average wave height

<table>
<thead>
<tr>
<th>Score</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave heights (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SeaStation®</td>
<td>0–1.47</td>
<td>1.47–1.61</td>
<td>1.61–1.76</td>
<td>1.76–1.90</td>
<td>1.90–2.04</td>
<td>2.04–2.19</td>
<td>2.19–2.33</td>
<td>&gt;2.33</td>
</tr>
<tr>
<td>Ocean Spar®</td>
<td>0–0.89</td>
<td>0.89–1.03</td>
<td>1.03–1.18</td>
<td>1.18–1.32</td>
<td>1.32–1.47</td>
<td>1.47–1.61</td>
<td>1.61–1.76</td>
<td>&gt;1.76</td>
</tr>
<tr>
<td>Corelsa®</td>
<td>0–0.6</td>
<td>0.6–0.74</td>
<td>0.74–0.89</td>
<td>0.89–1.03</td>
<td>1.03–1.18</td>
<td>1.18–1.32</td>
<td>1.32–1.47</td>
<td>&gt;1.47</td>
</tr>
</tbody>
</table>
This study made use of a predicted 15-year return period wave to create an extreme wave map. Alternatively, if a more conservative estimate was required, the value of the upper confidence interval limit could be used to generate this map. Importantly, measured time series of significant wave heights in the N Atlantic show an upward trend of 1–2% per year (Bauer, 2000). The reason for this trend is uncertain, but the possible damage to offshore cage structures might justify the use of more conservative values.

Fig. 14. Extreme wave height suitability map for (a) SeaStation®, (b) Ocean Spar®, and (c) Corelsa® cages.

Fig. 15. Average wave height suitability map for (a) SeaStation®, (b) Ocean Spar®, and (c) Corelsa® cages.

Fig. 16. Wave suitability map for (a) SeaStation®, (b) Ocean Spar®, and (c) Corelsa® cages.
Wavelength and period, which are not normally considered for site selection, are important wave effect features when designing offshore floating structures. It has been reported that the biggest wave does not necessarily produce the most severe loading (Cairns and Linfoot, 1990). Whittaker et al. (1990) concluded that longer period waves produced the highest mooring loads and the largest drift movements of the cage, while the shorter period waves produced the largest angular displacement of the joints. On the other hand, cage loads associated with longer ocean swells (greater wave length) have been found to be relatively small, while maximum forces are associated with shorter and more frequent waves generated by local storms (Isaacson et al., 1993). Also, the range of dynamic force on the mooring lines has been found to decrease significantly with increasing wavelengths. As the wavelength increases, the depth to which the wave loading penetrates also increases, which has an effect on the distribution of member forces in the top and bottom lines (Isaacson et al., 1993). Further model improvement could include the combined use of the wave heights and wave periods. For non-oceanic locations, the inclusion of current data together with bathymetry and seabed slope would give improved characterisation of marine conditions.

Although the implementation and use of GIS-based models for planning and management of aquatic resources is still developing, this study has shown it to be a powerful tool. It not only provided a visual inventory of the characteristic of the environment as thematic maps, but it allowed generation of suitability maps for different culture systems without complex and time-consuming data manipulation. An added advantage of using GIS for this type of studies are the efficiency of integrating a wide range of data and information sources into a compatible format. GIS provides a powerful tool for aquaculture system management and environmental monitoring. Integration of wave data within GIS for cage site selection proved very successful in this study, and shows the adaptability of GIS modelling for a range of spatial problems in aquaculture.

This study presents a methodology for siting offshore marine fish cages solely from the point of view of wave climate. Despite the fact that Tenerife was chosen as the study area, the developed methodology could be applied to any other coastal areas worldwide. For some areas, it is most likely that the source of wave data used in this study, forecast of wave models, will not be available and the model may need to be based upon data from buoys, wind or visual observation. Despite these differences, the framework and methodology should remain the same independent of the study location.

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