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Offshore mariculture: Site evaluation

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SUMMARY – The identification of suitable sites for marine aquaculture is an extremely important element in a successful commercial operation. The characterization of sites, in terms of exposure levels for systems and stock, will directly determine the options for use, and the types of technology and operating system which may be considered. For offshore mariculture, potentially with higher levels of routine exposure, such criteria may become critical. Based on longstanding experience at surveying and developing aquaculture sites in N Europe and the Mediterranean, this paper outlines some of the practical issues to be considered in evaluating sites and specifying their operational characteristics. Concepts are also developed to define the suitability of various cage system types for different site environments. Information is also provided on retrospective data to be obtained from loss analysis.

Key words: Marine sites, aquaculture, surveys, environments.

RESUME – *"Mariculture en mer ouverte : Evaluation des sites". L'identification de sites adéquats pour l'aquaculture en mer est un élément extrêmement important dans le succès d'une opération commerciale. Les caractéristiques des sites, en termes d'exposition pour le matériel et pour les animaux, vont directement déterminer les options à prendre et le type de technologie à utiliser. Pour la mariculture en haute mer, théoriquement plus exposée, de tels critères sont souvent cruciaux. S'appuyant sur une expérience de longue date dans le domaine du développement de sites aquacoles en Europe du Nord et en Méditerranée, cet article donne un aperçu des problèmes pratiques à considérer dans l'évaluation de sites et dans la spécification de leurs caractéristiques opérationnelles. Des concepts sont aussi développés, afin de déterminer si différents systèmes de cages sont propices à différents environnements.*

Mots-clés : *Sites marins, aquaculture, évaluations, environnements.*

Introduction

The development of offshore sites is potentially one of the more promising avenues for marine aquaculture in the Mediterranean, as elsewhere. However, sites require to be carefully evaluated as a basis for cage and mooring selection or design, and the offshore system must be chosen or developed to interact safely and effectively with site conditions (Beveridge, 1996).

In much of Europe, site surveys for mariculture are carried out separately, often by different agencies, and for different purposes. Pre-installation surveys may be carried out prior to a development, to assess feasibility, obtain local and national approvals, determine environmental impact baseline parameters, select location and orientation and choose equipment. Post installation surveys may be carried out to monitor performance or environmental impact. If a system failure occurs, there is generally a loss investigation, and evaluations may be made to consider how the system can be better set up or protected against future risks. Finally, further surveys may be needed if the project is to expand or if newer technology is introduced.

While this text is biased only towards site specific surveys intended as a basis for specifying suitable cages and moorings, a number of other issues are noted with respect to more general site assessment (see Table 1 below).

Preinstallation surveys

Many surveys will be carried out before any fish farm is installed. Indeed, many "greenfield" surveys have negative results, without resulting in any investment. Under government approvals, there are many areas of concern, including environmental, scenic, employment, health and safety and navigational impact. In many locations, aquaculture is still a "sunrise" industry, requiring increasing government administration and control. Under these circumstances, the mechanisms for approvals often lag behind the demand, leading to provisional approvals, which create difficulties for government and investors alike. Unless there are clear guidelines on policy areas, there can be conflict between national and regional policy.

Table 1. Data groups required for surveys

Data groups required	Greenfield survey	Government approvals	Cage and mooring selection	Insurance approval	Funding agents
Wind, wave and current forecast	• •	• • •	• • • •	• • •	• • •
Bathymetry	• •	• • •	• • • •	• • •	•
Seabed material data	•	• • •	• • • •	•	•
Seabed species data	•	• • •	•	•	•
Toxic outfalls, plankton data	• •	• • •	• • •	• • •	•
Local marine interests	•	• •	• •	• •	•
Local trade interests	•	• •	• •	• •	•
Shore-base availability	• •		• •	•	•
Local facilities and skills	•		• • •	• •	•

The starting point of an offshore aquaculture proposal may only be a region, a species to be farmed or a target of tonnage to be produced, to suit markets and the investor's objectives. Table 1 notes some of the survey data groups required for various interested parties, prior to the installation of a project. The number of points indicates approximately the quantity and quality of data required.

A number of other key decisions have to be taken by investors, prior to installing a cage system. These include a range of strategic matters such as workboat selection, storage, handling and processing facilities, training, health and safety provisions, etc., without which the project as a whole may not be sufficiently defined, and all of which modify input to, and influence outcomes of other surveys. A number of "desktop" assessments, based on limited site visits and general rather than site specific data may be carried out, and repeated/amended before a suitable "greenfield" site is found. It is a characteristic of such an initial site feasibility survey that it may produce negative results, and it is not practical that expensive and time-consuming assessment be made until the general feasibility is established (see Beveridge, 1996; Willinsky and Huguenin, 1996). Such studies are intended to produce data in order to answer the following questions:

Availability and approvals

(i) Is the likely environmental impact of a project likely to obtain local and national government approval?

(ii) Are potential fish growth and health parameters satisfactory?

(iii) Are there any local factors likely to change to adversely affect future approvals or fish health?

(iv) Is there a suitable (nearby) shore base for all necessary marine boat activity?

(v) What pool of local labour, both skilled and unskilled, is available?

(vi) What relevant local facilities are available?

Market, economic and risk factors

(i) Are local, regional, national and export markets sufficient for extra tonnages to be produced? Are the transport links sufficiently favourable, so that sufficient sales are not penalized?

(ii) Is the site under question suitable in terms of depth, wave climate and current climate, and could cages survive the worst storm conditions likely with a given probability?

(iii) Could fish survive the worst storm conditions likely with a given probability?

(iv)What would the estimated capital cost of suitable cages and moorings, and their installation, and what might be their estimated life?

(v) Can cages be worked economically?

Data which is in gross error in an initial survey can have an ongoing impact on future surveys, and might lead to dangerous underspecification of equipment. This is known to have been a problem, in farms where site surveys have been totally neglected, produced by cage manufacturers with a vested interest, or based on the use of trivial data. Short and long term consequences are usually disastrous, while costs of independent professional assessment are easily repaid in good project performance.

Detailed site surveys for specification of cages AND moorings

Important concepts

This is an extensive topic, and only the important concepts can be summarized in this text. Technical issues such as the statistical treatment of winds used for hindcasting, wave theory and the analytical process of mathematical wave modelling, the theory of structures for marine applications, tank modelling, fatigue failure in various materials (including ropes), corrosion, net drag coefficients, dynamic response and other topics require full time study in themselves (see, e.g., Carson, 1988; Rudi *et al.,* 1988; Cairns and Linfoot, 1990; Dean and Dalrymple, 1991; Herbich, 1992; Randall, 1997). Prior to discussing the main concepts at a practical level, the box below outlines some of the most important terms and definitions.

Key terms and definitions

(i) *Significant wave height* H_s: this is not the maximum wave height. Waves on a real site are not all of the same height, and can be approximated by wave spectra. The significant wave height is a spectral measure of the mean of the top third of wave heights in a period of time. It approximates to the wave height reported by observers, and to the "mean energy" wave. The maximum wave height may be between 1.8 and 2 times the significant wave height.

(ii) *Orbital wave particle motions*: during the passage of a wave at a point on the surface, the water particles move in an orbital path. In deep water (relative to wave length) these orbits are circular, the orbital period is equal to the wave period, and their orbital diameter is that of the wave height. An approximation to orbital particle velocities can be obtained by dividing the orbital diameter by the wave period.

(iii) *Wave hindcasting:* is a process of estimating wave climate from wind statistics combined with a knowledge of wind systems and fetch lengths.

(iv) *Mathematical wave modelling:* is an iterative process performed usually on a computer, whereby waves are progressed step by step from deep water, into shallow bathymetry. At each step, calculations are made of diffraction and refraction, plus the alteration in wave heights due to changes in wave energy. The wave is eventually progressed into the breaking and dissipation zones near the shore. If a model is to be accurate it requires good input data on incident deep water wave parameters, bathymetry and seabed "roughness". In some cases models are calibrated by taking actual wave parameter measurements.

(v) *Wave spectrum:* waves rarely if ever occur in their simple form, where each wave has the same wave height, period and wavelength of its predecessor. "Real" waves occur with small frequency variations and can better be analysed as wave spectra. Various wave spectra such as the Píerson-Moskowitch, and JONSWAP, which are tabulated with respect to fetch length and windspeed, have resulted from wave data analysis. These spectra can be used to make wave parameter predictions.

(vi) *Windspeed return period:* this is a term commonly used to define the probability of a windspeed event. For example, if a particular windspeed has a probability of being equalled or exceeded in any one year, of 0.02 (2%), then it is said to have a return period of 50 years.

A cage group, its nets, moorings and the plant used for husbandry are a linked system for the purposes of design, and cannot be properly considered in isolation (Kery, 1996; Lien *et al.,* 1996; Rudi *et al.,* 1996; Oltedal *et al.,* 1988). The specification of a suitable system must also be site specific. To consider cages alone is as futile as considering only the wheels of a car, without the remaining components, or without knowledge of the terrain over which it must travel. Furthermore, changes in cage orientation, in mooring response, in net weighting and flotation, all affect the dynamic response and performance of the system. It may be necessary to consider different options to accommodate specific site conditions. There have also been cases when farm workboats, or well boats have damaged cages, and or moorings, and some have resulted in major losses. It is important to know which boats will be used alongside cages, and under what conditions. During strong winds, for example, workboats may generate greater loads on moorings, than the maximum storm loads forecast.

The essential issue in evaluation is to define site conditions with respect to the physical characteristics of the potential cage system, to determine whether it will be feasible to consider, and if not, to consider whether amendments to design or site configuration could achieve the intended objectives. Key elements will be wind, wave and tidal current forces, described as follows.

Wind climate

Wind exerts considerable pressure on the exposed portions of a cage system and this pressure has to be resisted by the moorings and anchors. This is proportional to the square of the windspeed, and so a small increase greatly increases wind pressure. In high latitudes, these wind pressures can be extreme. For example, wind pressure for the 50-year return period (3-sec gust) windspeed in the Shetland Islands (54 m/sec) is some 1790 N/m^2 (or 182 kgf/m^2).

A typical plastic circle cage of some 60-metre circumference will expose around 18.5 metres of surface area normal to the wind flow and at a gust windspeed of 54 m/sec, the total load on the cage will be approximately 34 kN, or 3.4 tonne force. To maintain such a cage on station during this wind, a towing vessel of at least 500 hp would be required. Anchoring demands are clearly substantial.

Maximum storm and prevailing windspeeds

A developer may wish to know the maximum windspeeds to which a cage group is likely to be subject, over a given period, and will also require to know the common, day to day conditions. These latter conditions are likely to cause material fatigue and will also influence working practices of feeding and husbandry. For example, wave heights in excess of a metre mean that boats alongside a cage may cause cage damage.

Wind statistics

Wind speed statistics are available from a number of sources. Civil engineering publications and construction standards often publish maps showing contours of equal windspeed (isopleths) of a given return period (probability). Tabulated data on wind speed and direction are also available either from local meteorological stations (e.g., at airports), or from the central World Met Data Clearing House at Bracknell

> On one site, a reputable company produced a wave climate forecast of a 2 m significant wave height under storm conditions. Some 2 years after installation, an exceptional storm occurred, when gust windspeeds of 90 mps (325 kph) were recorded. Observations from the land estimated wave heights on the cages of around 14 m! The terminal freefall velocity of a body is around 56 mps (200 kph). During this storm, an uncautious observer might have been expected to be lifted off his feet, and flown across the ground at around 125 kph!

in the UK. By statistical treatment, such tabulated data can be used to make predictions of the probability of a given windspeed from a given direction. Wind "roses" are often used to display windspeeds for a given locality, displaying percentage frequency of winds of different strengths, around the 360º of a compass rose. This is a good method of pictorially summarizing prevailing windspeed data.

Gust and "steady" windspeeds

Winds do not blow steadily but have short-term peak values, or gusts, which indicate the peak windspeed maxima (Shellard, 1965). There is an approximate relationship between the 3-second gust, the 15-second gust, the 10-minute mean, and hourly mean windspeeds. For calculating instant peak wind loads, the 3-sec or 15 sec gust speed can be used, but for calculating wind driven wave heights, a longer period such as the mean hourly windspeed should be used. The 15-sec gust and hourly mean offshore windspeeds are approximately 90% and 73% respectively of the 3-sec gust speed, or conversely the 3-sec and 15-sec gust speed are 137% and 123% of the hourly mean windspeed. The 3 second gust is commonly used as the shortest windspeed measurement interval. This is because this is the shortest response time for conventional anemometers.

Wave climate

Accurate determination of wave climate is vital in determining:

(i) Which type of cage system will survive, and for how long.

(ii) What is the best orientation for the cages.

(iii) Whether or not fish will survive in storm conditions.

(iv) What type and strength of nets will be required to avoid storm damage.

(v) What mooring excursion – restoring force limits will be necessary to minimize cage and anchor loads.

(vi) What maximum peak mooring loads will occur, both at the top, and at the anchor.

(vii) Whether or not the cages will be workable on sufficient days.

(viii) The type of boats required for the farm.

(ix) What type of feeding system may be required.

(x) What offshore 'deep' counter currents may be generated by onshore storms.

> Engineering structures, including fish farms are designed to withstand maximum conditions, with a low statistical probability. A bridge might be designed to withstand an event predicted to occur with an annual probability of 0.002, that is a theoretical "retum period" of 500 years. Structures with a low probability of loss of life are designed to lower return periods. Fish farms may be based on a 50 year return period storm event. However, if global warming is changing conditions for the worse, previous calculations will be inadequate.

Orbital wave particle motions and water depth

During the passage of a wave at a point on the surface, the water particles move in an orbital path. In deep water (relative to wave length) these orbits are circular, the orbital period is equal to the wave period, and their orbital diameter is that of the wave height. Further down in the water column, the orbital paths decrease with depth, until at approximately the depth of 50% of the wavelength, the motions are analytically negligible. As the wave approaches shallow water, the seabed friction progressively damps the particle motions near the seabed, slowing the wave down. While the wave period remains constant, the wave length contracts, steeping the wave faces. A wave approaching depth contours at an angle will be more affected at one end than the other, and change direction in this area, in a process known as wave refraction.

Higher and steeper waves – Higher costs

In general, the higher the storm and prevailing wave climate, the higher the associated capital and operating costs for aquaculture systems. Not only must cages, nets and moorings be stronger, but boats must be larger and better equipped, maintenance is more difficult and travel time to and from such sites may argue for the use of a permanent feed barge on site. All husbandry routines are more difficult and take longer. For wave regimes of the same height, steeper waves also create more difficult conditions, with a greater number of cycles, and more rapid changes in float level and system forces, resulting in greater potential for wear and fatigue stress, and more difficult working conditions.

Offshore deep-water waves in exposed locations may be less damaging to some cages than steep inshore waves modified by shallow water effects and stronger currents. Breaking waves in particular, of the "plunging" type are particularly damaging. These are usually confined to waters considerably shallower than half the incident wave lengths. In general, long wavelength waves are most affected by shallow water, with the longest storm wavelengths breaking in more than 15 metres of water. The Mediterranean has long fetches and some relatively stable wind systems where winds blow in a similar direction for considerable periods. These conditions lead to extremely long wavelength seas and swells, which can create very severe conditions inshore.

Current climate

While the Mediterranean Sea does not normally have strong currents, areas with large diurnal tidal level ranges may have exceptional currents. In locations such as the W of Scotland, with narrow inlets and islands currents may flow at up to 11 knots. Even in the Mediterranean, currents of up to 2.5 knots have been encountered. Wind driven surface currents in the Mediterranean can also be quite strong and have been measured during storms at speeds approaching 1 knot.

Current drag forces

When a current flows past an object in its path, it exerts a drag force on the object. There are various types of current drag classified according to flow characteristics, such as laminar flow, turbulent flow and skin drag. The general equation for current drag (in dimension $_x$) is:

$F_x = ½. (C_x x \rho x A_x x V^2)$, expressed in kN where,
C_x = the drag coefficient,
ρ = mass density of seawater (in t/m^2),
A_x = area normal to the flow (m^2)
V = incident current velocity (in m/s).

The drag coefficient depends on the shape of the object, the wetted area, and surface "roughness". Drag coefficients are also modified by shallow water, relative to the depth of the structure and can be accessed from tables, which tabulate the result of various trials with different shapes. In general, drag forces due to current speeds encountered in the Mediterranean will be proportional to the area of the object presented normal to the flow, and also proportional to the square of the current velocity. While current drag at speeds of less than 0.5 knot are rarely either significant in terms of load, nor problematic for routine husbandry, higher currents speeds present a rapidly increasing problem. A current of 2 knots will generate drag forces 16 times as great as those for a 0.5 knot current. Similarly a 3-knot current will generate current drag loads 36 times as great.

Net drag forces

As a current passes through an open structure, such as a fish cage with nets, the current speed is reduced. Therefore downstream parts of the structure are subject to lower current velocity and smaller forces. The loads on downstream members or nets are calculated using a progressive "shadow factor", which reflects the decrease in drag. Calculating the drag on cage nets is further complicated by the fact that nets deform in currents, to present a more streamlined profile to the current. The more nets are weighted, the less deformation and consequent drag reduction occur.

Reciprocating wave particle velocities generate reciprocating net drag, but short period waves do not allow sufficient time for significant deformation and response. Therefore, net drag forces due to wave particle motions are generally calculated without net deformation being taken into account.

Bathymetry and seabed characteristics

Accurate knowledge of the depths on site, not just under the cages but also at the anchors and along the mooring riser lines, is vital to ensure sufficient depths under the cage nets, to calculate the appropriate length of mooring lines and to ensure that rising mooring lines do not come into contact with the seabed (if at all possible). In order to achieve these goals it is necessary to have a relatively close spaced sounding grid over the whole area to be occupied by anchors, moorings and cages. In addition, most farms seek to expand within a few years, and it is normally cost effective to extend the initial survey area to include possible adjoining expansion sites.

If the bathymetry is relatively shallow and complex, with underwater reefs, either on site, or in the offshore approaches, then incoming deep water, long wavelength waves will be modified by the shallow water, by the effects of refraction and diffraction. In order to obtain an accurate estimate of on site wave climate, mathematical wave modelling may have to be employed. For results with a useful range of error, this requires a more accurate depth grid than those normally available on commercial marine charts. If this situation exists, then the bathymetric survey should be extended out to depths of 50 metres or more in the offshore approaches. However, the sounding grid density can be reduced.

When the depth contour lines are plotted on a site plan, complex contours often indicate the likelihood of shallow sediments above rockhead or rocky areas. Raised bumps or steep gradients generally mean that drag embedment anchors cannot be used successfully, and that either rock pins or gravity anchors will be required. Also, steep gradients cannot normally be used for gravity anchors, which can slide downslope.

Knowledge of the seabed material is necessary in order to make an informed choice of anchor type, and also to predict the loads that the anchor may be able to carry. Samples may be necessary to obtain sediment density, and penetrometer reading may be used to indicate sediment strength. It is often very little extra effort to take some samples of seabed flora, and fauna, plus some redox (reduction/oxidation potential) readings for use in a "baseline" survey.

Site survey methodology

Certain data should be available prior to commencing the detailed survey. Much will usually have been collected for the original feasibility survey. Apart from species and proposed tonnages, this data should include maps of the area, lease area co-ordinates, initial concepts of cage types and numbers, and details of the working base to be used for the survey. However, some surveys may be undertaken without this information, or may even pre-date the granting of a lease. While certain elements are common to all site surveys, the methodology and emphasis on particular data areas will necessarily differ from site to site. For example, some sites may have difficult rocky ground for anchors, and require more detailed investigation, while a deep site may not need such detailed depth contours, etc. The site survey described below is in order to collect data, to achieve the following goals: (i) to select suitable cages for the wind, wave and current climate on site; (ii) to determine the optimum location and orientation of the cage group within the lease area; (iii) to design moorings for the cage group or groups; (iv) to ascertain the most favourable method of installing cages and moorings; and (v) to determine the likely requirements in terms of boats and plant for husbandry.

It is important that methodology should be repeatable, i.e., when a location has been decided, there must be sufficient records to permit the cage installation team to re-locate the planned site position, either for anchors or cages. Depending on equipment, GPS devices can be used to define positions with a moderate to good level of accuracy. Bearings can also be checked onshore from the offshore site positions. A photograph with visible transits may also provide a quick visual reference.

Position fixing and marking out

The method used to locate positions, firstly for a depth sounding grid, and later for location of cages and anchors, will depend on the size of the site, its distance from shore, and on the available technology. A good map of the adjoining land is usually a prerequisite for preparing plans, not only for the principal survey purpose, but also for regulatory marine and licensing agencies. The latter will normally require cage positions to be plotted on the national grid network employed in land surveying, while the former may require positions given in latitude and longitude. To avoid repeated surveys, appropriate co-ordinates should be used, to ensure land and sea data are correlated. Portable radios may simplify procedures in communicating to land to do so. Some position fixing techniques, in descending order of technology are shown below:

(i) *Course and speed:* Boat on known course at fixed speed. Timed sounding intervals.

(ii) *Hand bearing compass:* 2 compass angles of known shore marks, from each position.

(iii) *Baseline and offset:* Transit markers at intervals: distance off by measured line, or subtended angle.

(iv) *Plane table surveying:* Simultaneous position angle from different ends of a shore baseline.

(v) *Radar ranging:* From boat on known course: radar distance offshore or mark.

(vi) *Hyperbolic fixing system:* Decca or Loran C navigator system. Direct Lat. and Long. Read out.

(vii) *GPS system:* Satellite navigation system. Low accuracy (<150 m) due to system error.

(viii) *DGPS system:* GPS system with shore station for error correction. High Accuracy.

(ix) *Electronic Distance Meter:* Combined EDM and Theodolite "shoots" boat target. High Accuracy.

Low technology methods often require several observers, in signal contact. Many survey techniques make use of a measured baseline, running parallel to, and close by the shore. A site offshore requires either radar ranging, or one of the hyperbolic or GPS fixing systems. From a small island, a radial grid pattern might be used, but soundings become further apart at the larger radii. Where possible the latter 2 methods, DGPS or EDM should be used, to offer high accuracy and fast operation over long distances. When the more sophisticated packages are used, there is often software available to process the data, and assist the drawing of sounding plans.

Measuring currents

The principal reason for a current survey for design and specification of cages and moorings, is to determine likely maximum currents, which will generate the greatest drag loads, and be most likely to put fish stocks at risk from reduced net volume. The ancillary purpose may be to determine daily mean currents at various levels in the water column, from which some assessment of dispersion of cage debris may be made. The accuracy of current surveys is generally low, as the data is rarely taken for long enough to obtain a true picture of results.

In an area with high tidal ranges, it is necessary to measure tidal currents at the high and low range times of the lunar cycle, throughout the daily tidal cycle. Tide tables might be consulted to choose days with high tidal ranges, which may coincide with the equinoxes. In an area with low tidal ranges, such as the Mediterranean, maximum currents are only likely during or shortly after storms. Readings of daily currents within the water column, without storm measurements, are likely to be low, and will not offer a true picture of the dispersion of cage debris arising through offshore bottom counter currents during storms. Storm measurements are therefore necessary, if it is possible to obtain them. Failing this, wind driven storm surface currents might be estimated from wind statistics.

Methods of measuring currents range from drogue tracking, to sophisticated electronic current measurement packages, which can be left out on site, and whose data can be down-loaded rapidly by an "interrogation" probe, onto a computer diskette. Current surveys produce vast amounts of data, and much of this may be zero data, and trivial. A software processing method is highly desirable. For determining the dispersion of cage debris, simple drogue tracking can be especially appropriate, but multiple depth drogues are required, and several people are needed to measure positions and retrieve the drogues at periodic intervals. The principles of some current meters are noted below, in order of expected increasing accuracy:

(i) Propeller Logs: the revolutions of a small free running propeller are measured to give a speed reading. There may be 2 propellers (or 4) at right angles, to determine current direction, but the orientation to the flow is normally secured by use of a downstream vane.

(ii) Sonar Logs: 4 transducers are set facing each other in pairs, at the end of 2 orthogonal bars of known length. The difference in signal timing between the transducer pairs is used to calculate velocities in 2 orthogonal direction, and hence the orientation of the current flow.

(iii) Magnetic flux Logs: These devices measure magnetic flux past a fixed transducer. Once again, 2 transducers may be needed to calculate the direction of flow relative to a fixed orientation.

Depth sounding

While sounding by line and weight may provide a low tech method of depth measurement, it is extremely slow, particularly in depths of more than 10 metres. Modern echo sounders working on sonar principles are both cheap and accurate, and are almost universally used. Certain echo sounders can also provide an estimate of the type of seabed material, and are particularly useful if calibrated by sounding over areas of known material at specific depths. Some echo sounders provide a paper read-out of continuous soundings, other simply provide point digital readings, and perhaps a transient CRT picture of the seabed. The most sophisticated survey sounders will have multiple transducers, and provide for downloading data to a small Palmtop computer or PC.

Higher frequency transducers (~200 kHz) have a narrow "beam", and produce the most accurate depth readings, particularly on sloping contours. Lower frequencies transducers (<150 kHz) have a wider beam, but better bottom penetration of soft sediments, and give a better picture of seabed material. Very Low Frequency transducers (boomers) can be used to penetrate sediments to the rockhead (i.e., the base rock level), and are sometimes used in the construction industry to ascertain necessary pile driving depths.

Sample survey schedule

Table 2 below provides a general draft of a working schedule, describing the typical sequence of events. This will require modification for the circumstances of the specific site and planned fish farm. It is important also, of course, to ensure that all necessary equipment and staff are available over the intended time, that equipment is in good working order and has been checked and calibrated if necessary, and that any necessary authorizations to work on the site have been obtained. Co-ordination with tide cycles, and provisions for "waiting on weather" also need to be considered.

Sources of additional information

Because an accurate estimate of wave climate is crucial to a successful selection of cage type, any further information, or corroboration of the estimated wave climate, is necessarily valuable. Any measured data from the region, perhaps collected for projects in other industries, is of benefit. It is also well worth asking local fishermen of long experience, for their estimates of maximum storm waves, or of the wave heights likely in say a Force 8 gale. On certain shores, diver observations of large sand ripples may also be confirmation of the penetration of long wavelength seas to the area.

As it is difficult to estimate current maxima without a long duration study, any extra data on extreme conditions is also very valuable. Once again the evidence of local divers and fishermen, may be illuminating, and provide corroboration of storm current events.

Table 2. Sample survey schedule

No.	Operation	Method notes
1	Prepare lease area maps	Collect small scale land maps and marine charts. Plot the lease area co-ordinates: plot in a land reference station, and orientation. Locate the land station physically with a permanent mark.
2	Mark out the lease area accurately.	Various methods can be used for this purpose including radar ranging, distance lines and transits, DGPS systems and Electronic Distance meters. Use marker buoys to locate the corners of the lease area.
3	Take current measurements	A current meter should be used to take current measurements at either end of the proposed cage group, and perhaps at 2 positions outside the cage area. Readings should be taken at different depths in the water column. Readings should be taken during strong winds where possible, so that strong wind driven currents can be located. This may mean installing the meter for a relatively long period, for the best results.
4	Take and plot site depth soundings	These must be accurate and detailed, on a grid of perhaps 10 to 20 metres. The survey area should be considerably larger than the lease area, so wave boundary conditions, re-location, and expansion plans might be plotted for the future. Correct for tidal levels. Plot on a site plan, and insert depth contours.
5	Plot optimum cage group position.	This should take into account minimum depths under nets, preferred orientation for waves, and expected current through nets, for good water quality and growth. Plot the anchor positions according to depths and design.
6	Inspect seabed material	A diver inspection should be made of 2 transects below the cage group, and also at the anchor positions. This should be primarily to note seabed material, but might also be used to carry out epibenthic population and species sampling, for a baseline study. An underwater video camera is useful.
7	Examine shore facilities	Inspect facilities such as local harbours or loading jetties, and of local plant available such as mooring boats, cranes, etc., for installation of cages and moorings. Obtain information on local services available for fish farm operations.
8	Carry out local consultation	Consultation with local fishermen, trades and tourist organizations concerning potential problems, and co-operation. Determine navigation channels, navigation light and local marine safety requirements.
9	Determine local hazards	Consult regional plans for position of present and future sewage and chemical outclass. Determine past events of toxic plankton and disease. Examine relevant Municipal by-laws.
10	Obtain environmental data	Should good local wind data not be available prior to the survey, it will be important to have the best wind data possible for accurate hindcasting of offshore deepwater waves. Inshore wave climates and currents may have been measured for other local Marine projects, and the availability of this data should be investigated.

Evaluation of bathymetry, winds, waves and currents

This section deals with the processing of data collected in the dedicated specific site survey described above. Some description of the presentation of data required has taken place in the earlier sections. This section is intended to describe in rather more detail, the data processing required, specifically to meet the survey goals outlined earlier.

Table 3 below shows more processing and tabulations than may be necessary for every site. Thus, mathematical wave modelling is not needed in well sheltered locations, nor where the cages are to be placed in deep water. In the following table, storm maximum events should be tabulated for a return period of ≥50 years.

Table 3. Data development requirements

Survey data	Tabulation or presentation required
1a Wind data	Storm maxima: 3-sec gust. direction, windspeed Prevailing winds: wind rose
1b Bathymetry	Depth plan: corrected for tide levels: cage and anchor, area Depth plan: shallow approaches from deep water
2a Offshore deep water wave climate	Storm maxima: direction, H_s, period, wavelength
2b Inshore wave climate on site	Prevailing waves: wave rose Predominant prevailing waves: H_s, period, wavelength
2c Wave modelling: input from 2a>>	Storm maxima: direction, H_s, period, wavelength
3a Current data	Maxima: Speed and direction over 30-day minimum Prevailing: Speed and direction: various depths
3b Standard formulae and input from 1a>>	Calculation estimation of storm wind driven currents
4a Seabed material	Site plan: Areas-. Sediments, corals, rock, sea grass, etc. Flora and Fauna: sample population data Redox readings and transect video
4b Sediment and rock strength estimate	Sample data and anchor efficiency conclusions

Cage type selection

This section deals with how the processed survey data is used to evaluate the survey goals cited earlier, and also to answer some of the questions posed initially. The most important of these goals is: (i) to select suitable cages for the wind, wave and current climate on site; and (ii) to determine the optimum location and orientation of the cage group within the lease area.

After processing site survey data, there may well be uncertainties or notable ranges of error, leading to further options in system choice and design. The surveyor/designer may look for additional input to determine the optimum choice. Further constraints may also emerge during the design process, whether financial, regulatory or environmental, influence final choices.

Classification of fish cage types

There is a wide array of alternative types of cage available, and new designs are brought out regularly (see also Scott and Muir, this volume; Christensen – practical development of offshore mariculture systems: the Irish experience, this volume; Basurco *et al.,* this volume). Regrettably, less testing may be carried out for those types which are copies based on earlier development work of another manufacturer. To some extent new developments and copies are based on experience of past failures which get into the public domain. Others attempt new technology, sometimes transferred from small-scale versions of structures used in the offshore oil industry, where a massive amount of R&D has been carried out. However, it is impossible to make even a simple approach to choice of cage system, without first attempting to classify available cages.

In many cases the choice may offer options in which higher (financial) risks are balanced by higher (financial) gains. This phase of final system choice requires consultation between investors, and the system designer, who should clearly define choices available, and attendant risks. For example, a non-proven system may offer a potentially better solution, but limited guarantees of success. This situation occurs in mariculture regularly, as new designs are continually being offered to the farmer. Many disasters have occurred where new, radical ideas have been adopted. Conversely, the industry cannot progress without adopting new ideas, many of which have offered significant benefits, and ultimately proved to be sound in conception.

In conditions of fiscal prudence, and compulsive litigation, few small organizations can afford high risks, unless properly funded and insured. One means of reducing risk on an experimental system is to monitor the internal cage and mooring loads, so that if severe conditions show the design loads have been approached, then modifications can be made (Marintek, 1987; Oltyedal *et al.,* 1988; Rudi *et al.,* 1996;). Also cage designs can contain factors for contingencies, such as perimeter ropes on plastic circles, or containment nets.

There has been a steady movement to site cages further offshore. This move was originally endorsed by the Royal Norwegian Council of Science, which cited a number of offshore advantages, and inshore constraints, which had lead them to this conclusion. European marine aquaculture started in sheltered waters, as technology at the right price did not exist to maintain them safely in higher wave climates. The advantages of inshore sheltered farms are obvious, cages can be less rigorously engineered and moored, stock, staff, feed and harvested product are transported over smaller distances by smaller craft, and security is generally simple. Various pressures are now pushing the mariculturist further offshore. There are the various lobbies of other water users, the question of scenic impact, the regulatory authorities, and the environmental agencies. But more significantly, the increase and rapid transmission of endemic diseases from area to adjoining area, has resulted in a general movement further offshore. While it is increasingly recognized that high stocking densities in relation to water quality parameters have a major impact on disease levels and prognosis, 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 costs of production. Such an offshore trend can also bring benefits, with better growth rates, less disease and potential economies of scale. However, there are problems as yet unsolved:

(i) Cages and moorings must be more heavily engineered, and each unit, albeit potentially larger, must require a higher "quantum" of capital cost, and a higher operational cost, given the distant location and greater exposure.

(ii) Larger better equipped boats and certificated crews are required, or more operations will have to be automated. A combination of both is likely. There is a problem getting people aboard an offshore installation, even in relatively good weather.

(iii) If economies of scale are to be exploited, the difficulties and scale of feeding such large, remote pens, on sites where there is daily wave motion, cannot be addressed by the present methods. Similar difficulties apply to the less frequent but necessary husbandry operations of grading, harvesting, net changing, and maintenance.

(iv) Greater wave motion increases relative motion between water and nets suspended from a slow moving collar, which is required to permit staff to operate in rough weather. The relative motion not only requires much stronger net enclosures, but also may cause de-scaling of fish during storms, with consequent, osmotic trauma and mortalities.

Offshore wave climates are substantially greater than inshore, and both the likely highest waves over a 50-year period, and prevailing or average wave heights will be larger. The former may cause instant total failure, the latter will promote gradual failure or reduced life through fatigue. Present cage designs can be roughly classified by common design factors and acceptable wave climates. However, while wave height figures to which specific cages have been exposed without failure, are known to the author, this does not mean that all such cages can survive these conditions, nor that such cages may have a long life at those exposures. Classifications as shown in Table 4 are subjective, and should not be used without a manufacturer's warranty for such conditions.

Some plastic circle cages have been given an offshore designation, and have probably survived storm wave climates in excess of Hs = 3.5 metres. However, there is little empirical or theoretical data as yet, to offer complete confirmation of conditions they may be expected to survive on a long-term basis. Figures for the "new generation" cages are initial estimates only, as there is insufficient data, and too many differing generic sub-types, to permit anything more than educated guesswork. Also while the cage structure may survive the conditions shown, the fish may not.

The final choice is usually dependent on finance available, as well as site data. The installation of newer cage systems may well be confined to existing fish farms, with better data on the expected conditions, and a good production history. The first stage of a choice is to classify a site according to its offshore storm wave climate, prevailing wave climate, and water depth. Table 5 below is a more detailed cage classification, the type numbers being used in the site classification Table 6.

Table 4. Cage design factors

Cage type and size	Pen volume enclosed m^3	Max H_s: 50 y RP	Mean H_s 40% days	Distance off km	Notes
Conventional cages:					
Square timber: 6-l2 m square	<1,000	0.8 m	0.2 m	<0.5 km	Cheap
Square steel: hinged: 12-15 m square	<2,700	2.0 m	0.4 m	<1.0 km	Low labour
Plastic Circles: 12-2 5 m ∅	<3,600	3.5 m	1.2 m	<1.0 km	Low capital
Flexible hose cages: square: 15-20 m	<4,800	5.0 m	1.4 m	<2.0 km	Auto feed
Flexible hose cages: hex: 20-25 m ∅	<10,700	6.0 m	1.5 m	<2.0 km	Auto feed
Steel tubular: hinged: 20 m square	<12,500	6.0 m	1.5 m	<2.0 km	
Semi-submersible	<10,700	10.0 m	1.8 m	<5.0 km	Auto feed
Some new generation cages:					
Rigid multiple pen barges: n x 20 m	n x 5,000	5.0 m	2.0 m	<10 km	Live aboard
Semi-submersible barges: n x 20 m	n x 5,000	6.0 m	2.0 m	<10 km	Live aboard
Tension leg cages: submerged	<10,000	15.0 m	2.0 m	<20 km	Telemetry
Seabed bottom structures	<2,000	15.0 m	2.0 m	<20 km	Telemetry

Table 5. Cage type classifications

Cage type	H_s max (m)	H_s 40% (m)	Type No.	Notes on limitations–advantages[†]
Conventional cages				
Square timber: 6-12 m	<0.8	0.2	C 1	Rigid, limited buoyancy: -low cost (LC)
Square steel: hinged: 12-15 m	<2.0	0.5	C 2	Prone to fatigue: -easy to operate (EO)
Plastic circles: 12-25 m ∅	<3.5	1.0	C 3	Difficult husbandry (DO)-(LI)-(LC)
Offshore P circles: 20-30 m ∅	<4.5	1.2	C 4	Need feed system: (DO)-(LI)-(LC)
Flex hose cages: 15-20 m	<5.0	1.5	C 5	Need feed system: (DO)-(LI)-(MC)
Flex hose cages: Hex: 20-25 m ∅	<6.0	1.6	C 6	Need feed system: (DO)-(LI)-(MC)
Steel tubular: hinged: 20 m	<6.0	1.2	C 7	High maintenance: (HC)-(CI)-(EO)
Tension spar: 20 m	<6.0	2.0	C 8	Need feed system: (DO)-(LI)-(MC)
Semi-submersible: Hex: 20 m ∅	9.0	1.8	C 9	Net change: harvest difficult: (CI)-(EO)
New generation cages:				
Rigid multi-pen barges: n x 20 m	<5.0	2.0	E 1	Prone to fatigue: Fish abrasion: (HC)-(EO)
Semi-sub barges: n x 20 m	<6.0	2.0	E 2	Limited capacity: (CI)-(HC)-(EO)
Submerged cages: –2 <depth<–5	<6.0	2.0	E 3	Not enough data:
Tension leg cages: submerged	<10.0	2.0	E 4	Not enough data: Good potential
Tension leg cages: pull down	<15.0	2.0	E 5	Not enough data: Good potential
Seabed bottom structures	<15.0	2.0	E 6	Unsuitable for shallow water: (HC)

[†]EO: Easy to operate; DO: difficult to operate; LI: labour intensive; CI: capital intensive;LC: low cost; MC: medium cost; HC: high cost.

In Table 6 below, the lower limits of wave climate are arbitrary, to suggest the sensible lower limit in which a cage should be deployed, on financial grounds. While all cages could be placed on any low wave climate site, but this would be a waste of technology and investment. A range and a mean value for storm wavelength and period, designated by λs max and τ s, are shown. A given significant wave height might have different wave lengths, depending on the generating combination of wind speed and duration. The table is simplified for presentation, but it is hoped that the general principles of selection emerge. Each square in the Matrix, which represents a site classification, can be identified using the combined Row and Column numbers.

Table 6. Suitability of cage types for different environments

Storm wave climate 50 year return period	Row	λs max[†] rnetres COL >	τ S sec	Depth m	Depth m	Depth m	Depth m	Depth m	Depth m
				8-12 1	13-20 2	21-30 3	31-50 4	50-80 5	>80 6
Storm H_s: 0.4<H_s <0.8 m	1	12-25	3.5	C 1-3	C 1-3	C 1-3	C 1-3	C 1-3	E?
Storm H_s: 0.8<H_s <1.5 m	2	25-45	4.7	NO	C 2-3	C 2-3	C 2-3	C 2-3	E?
Storm H_s: 0.8<H_s <2.0 m	3	40-55	5.5	NO	LIMIT	C 2-3	C 2-3	C 2-4	E?
Storm H_s: 1.0<H_s <3.5 m	4	69-95	7.3	NO	NO	C 3-5	C 3-5	C 3-5	E?
Storm H_s: 1.4<H_s <4.5 m	5	95-110	8.1	NO	NO	LIMIT	C 4-6	C 4-6	C4-6 E?
Storm H_s: 2.0<H_s <5.0 m	6	110-125	8.7	NO	NO	LIMIT	C 5-8	C 5-9	C5-9 E?
Storm H_s: 2.0<H_s <6.0 m	7	135-150	9.6	NO	NO	NO	C 6-9	C 6-9	C6-9 E?
Storm H_s: 5.0<H_s <8.0 m	8	180-190	11.0	NO	NO	NO	LIMIT	C 9 E?	E 4-6
Storm H_s: 5.0<H_s <10.0 m	9	195-260	13.0	NO	NO	NO	NO	E 4-6	E 4-6
Storm H_s: 5.0<H_s <15.0 m	10	400 +	16.0	NO	NO	NO	NO	E 4-6	E 4-6

[†]Note: λs max = storm wavelength; τ S = wave period.

The above tables do not take into consideration fish health relating to say, disease, exposure to toxicity and growth. However, environmental issues, fish health considerations and other issues also seem to be pushing the farmer further offshore. Some of the key questions the designer and investor should be asking themselves, are tabulated below (Table 7). The range of accuracy of the answers is also crucial.

Table 7. Key issues for practical operation

Factor	Issues
Survival: fish, cages and moorings	Is the cage site subject to breaking waves? Will the fish survive the probable storms? Would the fish survive a partial cage failure? What is its probability of survival? What is the best orientation of the cage group? How long will it last before requiring replacement?
Routine husbandry: simplicity and cost	What harbours are available for a marine base if any? What size and type of workboats will be required? How many days of feeding and husbandry are likely to be lost through weather limitations? After how long will the site need fallowing, if at all? What are the capital, operational, maintenance and probable replacement costs?
Personnel and safety	How safe are the cages for routine husbandry? What training will be required for the routine tasks?

Post installation surveys

Surveys do not stop with the installation of a fish farm, and ongoing data collection is required by the interested parties. It may be noted in the previous table, that data on wind, waves and currents was of prime importance. This is because these elements are the key to proper design for survival, not only of the cages, nets and moorings, but also of course the fish stocks! It is true to say that there have been many cases of the storm survival of cages, nets and moorings, while the fish have suffered such damage that they died. Conversely, in some damaged systems, cages and nets were a total loss, but the fish stocks remained on site, around the cage debris, waiting to be fed!

Range of wave climate prediction errors

However, offshore, or deepwater wave climate data, which categorizes the waves likely to be incident on the offshore boundary of a fish cage site, is usually produced as a forecast from available wind statistics, by the process of "hindcasting". The data may be further processed (by mathematical wave modelling), to examine how the waves will be affected by shallow waters, as it approaches the site. Both these analytical processes have a range of errors, which can be decreased by the improvement of the input data. As is often said about data processing, and statistical predictions, "Garbage in... ...garbage out!" – and so it is important to be aware of where limitations lie.

Monitoring of empirical data: Confirmation of estimated data

Cages and moorings are designed for low probability rare maximum environmental conditions (see also Turner – offshore mariculture: mooring system design, this volume). There is generally therefore sufficient time following an installation, to gather empirical site data, which can confirm or otherwise the accuracy of the predicted data used in the design calculations. This in turn leads to the opportunity to verify that the installation as designed is adequate, and if not, to carry out modifications to increase the chances of survival. Table 8 outlines some of the key issues and those functions for which data would normally be required.

Table 8. Data groups required for post-installation surveys

Data groups required	Maintenance inspection	Environmental impact	Health and safety	Insurance renewal	Funding agents
Wind, wave and current data	•	•	• • •	• • •	• • •
Cage and mooring performance	•	•	• • •	• • •	•
Seabed material data	•	• •	• • •		•
Seabed species data	•	• •			•
Toxic sources: disease data	•	• •	• • •	• • •	•
Local marine and trade interests	•	• •	• •	• • •	•
Personnel and training	•		• •		
Markets and profitability			• • •		•
Expansion potential			• • •	••	•
Loss and accident investigation	• • •	• • •	• • •	• • •	• • •

NB: It may be noted that insurers and investors have perhaps the highest stake in the survival of a farm and their ongoing scrutiny is vital.

Similarly, the environmental regulators will seek to monitor the environmental impact of the cages, and to compare it with the original "baseline" study. Once again, remedial actions like fallowing a site, or benthic suction "dredging" may be carried out, to prevent permanent or long term damage.

Cage failure and loss investigation

Structural failures occur, and accidents happen on fish farms, as in any other walk of life. Following any such incident there will be an investigation, which should result in improved structures or methods. It is true to say that every design is based on knowledge of past failures, and the treatment of an investigation, its documentation, and accessibility to future designers and regulators is crucial. The implications of a fish farm loss are always severe, not only for the underwriters, but more particularly for the investors and the farm personnel. Where a cage system has broken up, it may create a hazard; navigational, environmental or scenic. Deep water and nets often combine to make salvage an expensive and sometimes dangerous task.

After a major loss, a fish farm may become bankrupt, and unable to pay for necessary salvage. However, few sunken fish farms in deep water constitute an environmental hazard, except perhaps through the mixing of farmed and wild fish stocks. Most wrecks become rapidly covered in marine growth, making a good habitat for various species. While salvage of sunken oilrigs has become a political "cause celebre", it may be unwise to place the same emphasis on the retrieval of broken cages from deep water.

At the present, in many parts of Europe, underwriters pay for loss investigation. They therefore regard the information concerning the causes of a loss, as commercially valuable property, and are reluctant to allow access to other parties. This in turn means that few can benefit from the knowledge of causes of loss. This is in contrast to accidents in public transport or aviation, where investigation is frequently conducted by government or internationally sponsored agencies, such as the Civil Aviation Authority, or the Marine Safety Agency in the UK. Fundamental research into the causes of losses is also undertaken by centrally funded laboratories. This ensures that both loss data and fundamental research are firstly undertaken by independent agencies with no vested interest, and secondly, that loss investigation data is in the public domain, where it can be used by system designers, to improve the ’breed’ of existing systems.

General conclusions

In recent years, there have been a number of seminars in the UK and elsewhere, where there has been limited sharing of loss information, and attempts to obtain some cross-fertilization between engineers and designers. This has lead to a number of initiatives by designers to improve fish cage designs. The various surveys being carried out by different organizations, with different goals, often collect the same data more than once. This data overlap is both costly and can cause delays. The quality of data collected for discrete areas may be of variable quality and cannot readily be compared with data from adjoining areas.

Causes of losses, and loss investigations should be in the public domain, just as in the public transport and aviation industries. There is a strong case for centralizing the collection of some of the coastal data in a national mariculture database as suggested in Table 9. While much of this data may be available in various publications, its availability to investors may be limited, unless such a database is compiled. This data might be collated for similar zones.

Table 9. Data potentially suitable for a national mariculture database

National database	Environmental data (collated for coastal regions, by similar zones)
Windspeeds and directions	Wind roses and durations: storm events compiled by return period probability
Offshore wave climate	Deepwater incident wave parameters: hindcast or empirical wavebuoy data
Inshore wave climate	Wave modelling results: collation of mathematical wave modelling results
Current climate	Current time and direction: wind driven: longshore drift: through water column
Bathymetry	Coastal charts: upgrading by small scale surveys: related to a national grid
Seabed material	Rock or sediment: an extension of small-scale geological benthic mapping
Seabed flora and fauna	Rare species and wild stocks: mapping occurrence and population indicators
Toxic plankton: disease	Local pathology: chemical and sewage outfalls: toxic bloom and disease records
Local marine activity	Navigation: fishing and tourism: nav. Channels: regional plans: local trade
Loss investigation data	Fish farms and wreck: location and contents of wreck: prime cause of loss

Such a database could probably only operate under strong national as opposed to regional aquacultural policy. However, a national policy would have the benefit of consistent application, as well as the following: (i) overall savings would result from not duplicating data collection; (ii) a data access fee could be charged to potential investors, insurers, etc., to fund the database; (iii) better available data for feasibility studies would reduce the chance of errors and save time; (iv) today's unsuitable sites, may be tomorrow's best sites, due to advances in cage technology; (v) arguments between environmental agencies, insurers, and fish farm engineers are minimized; (vi) the data is gathered by an independent source with no vested interest; (vii) anomalies between regional data can be exposed by comparison; (viii) cage installations provide potential permanent, empirical, data collection stations, at low cost; and (ix) coastal engineering would benefit from improved, linked environmental data.

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