# Three-dimensional hydrodynamic models coupled with GIS-based neuro-fuzzy classification for assessing environmental vulnerability of marine cage aquaculture.

**THESIS SUBMITTED TO THE UNIVERSITY OF STIRLING**

**FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

By Juan Moreno Navas MSc

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UNIVERSITY OF
STIRLING

***To my family***

## Declaration

I declare that this thesis has been composed in it’s entirely by the candidate. Except where specifically acknowledged, the work described in this thesis has been conducted by me, it has not been submitted for any other degree and the work of others has been properly cited.

Signature: ________________________________________

Signature of supervisor: ________________________________________

Date: ________________________________________

## Abstract.

There is considerable opportunity to develop new modelling techniques within a Geographic Information Systems (GIS) framework for the development of sustainable marine cage culture. However, the spatial data sets are often uncertain and incomplete, therefore new spatial models employing “soft computing” methods such as fuzzy logic may be more suitable.

The aim of this study is to develop a model using Neuro-fuzzy techniques in a 3D GIS (Arc View 3.2) to predict coastal environmental vulnerability for Atlantic salmon cage aquaculture. A 3D hydrodynamic model (3DMOHID) coupled to a particle-tracking model is applied to study the circulation patterns, dispersion processes and residence time in Mulroy Bay, Co. Donegal Ireland, an Irish fjard (shallow fjordic system), an area of restricted exchange, geometrically complicated with important aquaculture activities.

The hydrodynamic model was calibrated and validated by comparison with sea surface and water flow measurements. The model provided spatial and temporal information on circulation, renewal time, helping to determine the influence of winds on circulation patterns and in particular the assessment of the hydrographic conditions with a strong influence on the management of fish cage culture.

The particle-tracking model was used to study the transport and flushing processes. Instantaneous massive releases of particles from key boxes are modelled to analyse the ocean-fjord exchange characteristics and, by emulating discharge from finfish cages, to show the behaviour of waste in terms of water circulation and water exchange.

In this study the results from the hydrodynamic model have been incorporated into GIS to provide an easy-to-use graphical user interface for 2D (maps), 3D and temporal visualization (animations), for interrogation of results.

Data on the physical environment and aquaculture suitability were derived from a 3-dimensional hydrodynamic model and GIS for incorporation into the final model framework and included mean and maximum current velocities, current flow quiescence time, water column stratification, sediment granulometry, particulate waste dispersion distance, oxygen depletion, water depth, coastal protection zones, and slope.

The Neuro-fuzzy classification model NEFCLASS–J, was used to develop learning algorithms to create the structure (rule base) and the parameters (fuzzy sets) of a fuzzy classifier from a set of classified training data. A total of 42 training sites were sampled using stratified random sampling from the GIS raster data layers, and the vulnerability categories for each were manually classified into four categories based on the opinions of experts with field experience and specific knowledge of the environmental problems investigated.

The final products, GIS/based Neuro Fuzzy maps were achieved by combining modeled and real environmental parameters relevant to marine fin fish Aquaculture.

Environmental vulnerability models, based on Neuro-fuzzy techniques, showed sensitivity to the membership shapes of the fuzzy sets, the nature of the weightings applied to the model rules, and validation techniques used during the learning and validation process. The accuracy of the final classifier selected was R=85.71%, (estimated error value of ±16.5% from Cross Validation, N=10) with a Kappa coefficient of agreement of 81%. Unclassified cells in the whole spatial domain (of 1623 GIS cells) ranged from 0% to 24.18 %.

A statistical comparison between vulnerability scores and a significant product of aquaculture waste (nitrogen concentrations in sediment under the salmon cages) showed that the final model gave a good correlation between predicted environmental vulnerability and sediment nitrogen levels, highlighting a number of areas with variable sensitivity to aquaculture.

Further evaluation and analysis of the quality of the classification was achieved and the applicability of separability indexes was also studied. The inter-class separability estimations were performed on two different training data sets to assess the difficulty of the class separation problem under investigation. The Neuro-fuzzy classifier for a supervised and hard classification of coastal environmental vulnerability has demonstrated an ability to derive an accurate and reliable classification into areas of different levels of environmental vulnerability using a minimal number of training sets.

The output will be an environmental spatial model for application in coastal areas intended to facilitate policy decision and to allow input into wider ranging spatial modelling projects, such as coastal zone management systems and effective environmental management of fish cage aquaculture.

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# Chapter 1 General introduction.

Aquaculture is the fastest growing food production system on the planet and accounted for 47 percent of the world's fish food supply in 2006. World aquaculture has grown tremendously during the last fifty years from a production of less than a million tonnes in the early 1950s to 51.7 million tonnes by 2006 (FAO, 2008) (Fig 1.1).

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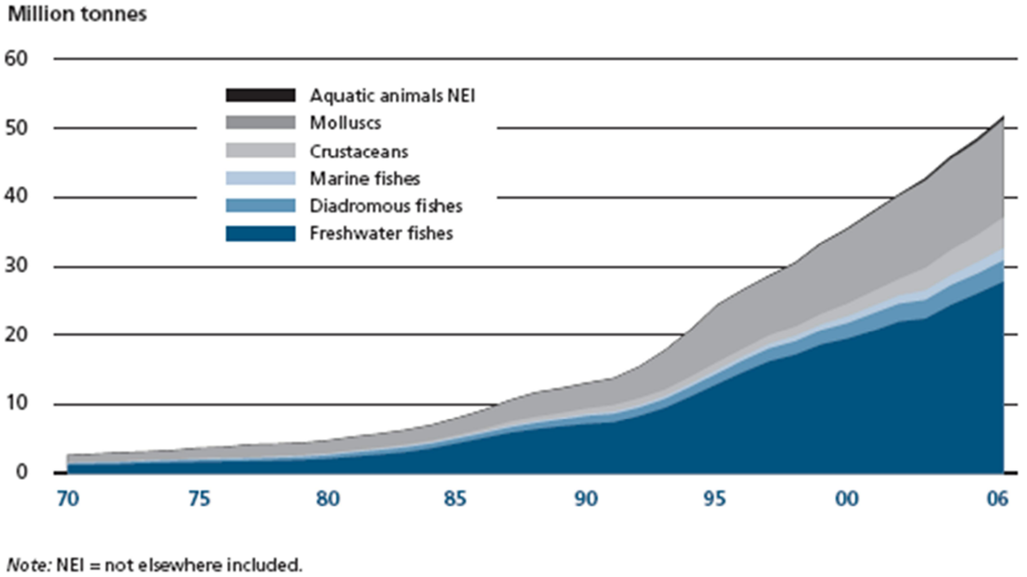

**Fig 1.1. Trends in world aquaculture production: mayor species groups from FAO (2008)**

In 2004, aquaculture production from mariculture was 30.2 million tonnes, representing 50.9 percent of the global total. Freshwater aquaculture contributed 25.8 million tonnes, or 43.4 percent of the total. The remaining 3.4 million tonnes, or 5.7 percent, came from production in brackish environments. (FAO, 2006).

According to FAO projections (FAO, 2002), it is estimated that in order to maintain the current level of per capita consumption, global aquaculture production will need to reach 80 million tonnes by 2050.

Salmon is one of the most popular food fish species in the United States, Europe, and Japan, and salmon aquaculture has increased over the past decades to meet this market demand. In 1980 farmed salmon made up a negligible percentage of world salmon supply, but by 2003 approximately 60% of global salmon supply was farmed. In aquaculture, the Atlantic salmon (*Salmo salar*) represents 90% of production and is by far the most economically important cultured salmon, currently being produced in 24 countries. The major producers of salmon are Norway, Chile, the United Kingdom, and Canada, although Chile and Norway account for close to 75% of farmed salmon production (FAO, 2006), but an ongoing outbreak of the virus infectious salmon anemia, ISA and an accelerated harvesting have led to a drop from 650,000 tons to 400,000 tons of Chilean salmon, according to Gallardo (2010).

## 1.1 Integrated Coastal Zone Management and aquaculture.

Clearly, if aquaculture is to grow as predicted by FAO, then there will be increasing pressure on space. This applies to continental aquaculture as well as to developments in the coastal zone. The coastline has traditionally attracted a very large proportion of the world’s human population. This growing population demands, competes and generally uses the coastal space, frequently in an incompatible way and placing continually increasing pressure on coastal resources. The United Nations conference on environment and development (UNCED) in Rio de Janeiro in 1992 developed the concept of Integrated Coastal Zone Management (ICZM) in order to tackle the urgent need to manage littoral and sub-littoral zones. The development and approval of coastal aquaculture projects should be based on ICZM principles, taking into account the use of, and conflicting demands upon, identified resources while simultaneously supporting coastal livelihoods and tourism, protecting marine habitats, and preserving ecological functions and biodiversity (Perez, 2003).

## 1.2 Introduction to Geographic Information Systems.

For the implementation and development of ICZM policies it clear that decision making requires access to appropriate, reliable and timely data. Almost without exception, this information has a spatial component and Geographical Information Systems (GIS) have a clear role in managing such data. A GIS is a technological tool for comprehending geography and making intelligent decisions, (ESRI, 2008). Burrough, (1986) and Kapetsky and Travaglia (1995) defined GIS as an "integrated assembly of computer hardware, software, geographic data and personnel designed to efficiently acquire, store, manipulate, retrieve, analyze, display and report all forms of geographically referenced information geared towards a particular set of purposes".

The world's first GIS was developed in the 1960s and 1970s in Canada, by the federal Department of Forestry and Rural Development. This was called the "Canada Geographic Information System" (CGIS) and was used to store, analyze, manipulate and display data collected for the Canada Land Inventory (Jones, 1997).

Nath et al. (2000) categorized several phases in a GIS project: identifying requirements, formulating specifications, developing the analytical framework, locating geodata sources, organizing and manipulating data sets for initial input, analyzing data and verifying outcomes, and finally evaluating the spatial outputs.

Geographic location is the key for much of the potential of GIS, which has the ability to map and to tie together with a common referencing system different kinds of information from several sources, scanning, air borne image, satellite images etc, because they geographically refer to the same place (Fig 1.2). The location attributes use coordinates stored digitally and GIS is therefore structured around a straight forward X,Y co-ordinate system (LAT/LONG, UTM, etc) to which a number of thematic layers such as socio-economic, environmental, military information can be referenced (Fig 1.2). GIS represents real world objects (land use, elevation, etc) with digital data. Real world objects can be divided

into two abstractions: discrete objects (e.g. aquaculture cages and roads) or continuous fields (e.g. salinity or temperature). There are two main methods used to store, manipulate and display data in a GIS, Raster and Vector (Longley et al., 2005). Raster data consists of rows and columns of cells, with each cell storing a single value. Raster data can be images (raster images) with each pixel (or cell) containing a numerical or colour value. Vector data considers all features as geometrical shapes and geographical features are expressed by different types of geometry; points, lines, polylines or polygons.

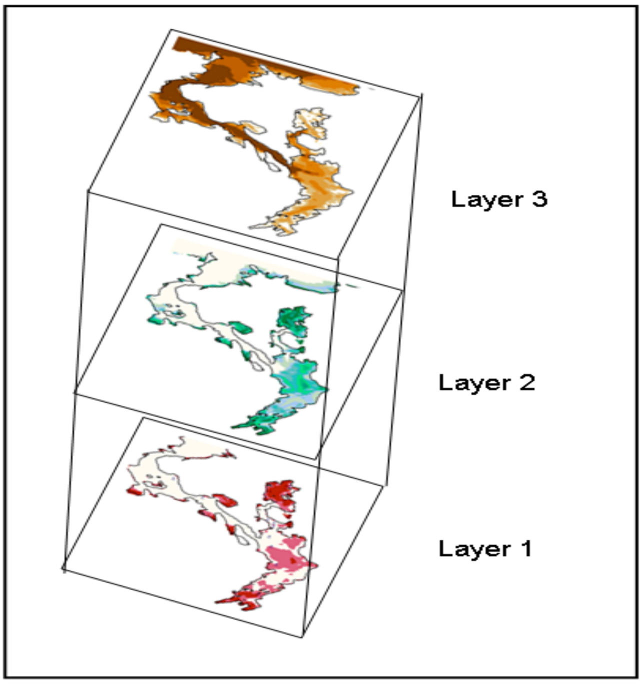

**Figure 1.2. Geographical data layers**

## 1.3 GIS in Aquaculture.

The spatial information needs for decision-makers and planners developing aquaculture, are well served by geographical information systems (Kapetsky and Travaglia, 1995), The technology is a proven tool for natural resource management and space planning and should be used extensively for planning in aquaculture (Dempster and Sanchez-

Jerez, 2008). GIS also allows information management without complex and time consuming manipulations (Wright and Barlett, 2000).

GIS application in aquaculture has targetted a broad range of species and well as geographical scales ranging from local areas (Ross et al., 1993; Scott and Ross 1999) to sub national regions and islands ( Aguilar-Manjarrez and Ross, 1995; Goulletquer and Le Moine, 2009; Perez et al., 2005) to nations (Arid et al., 2005; Salam and Ross, 2000) to geographical areas (Guneroglu et al., 2005; Aguilar-Manjarrez and Nath, 1998) and world wide (Handisyde et al., 2006). Specific topics have included site selection for target species such as molluscs, (Chenon et al., 1992; Krieger and Mulsow, 1990; Scott et al., 1998; Arnold et al., 2000; Halvorson, 1997) crustaceans (Alarcon and Villanueva, 2001) fish (Benetti et al., 2001; Perez et al., 2005; Perez, 2003) seaweeds, (Brown et al., 1999) environmental impact assessment (Fuchs et al., 1998; Gupta 1998; Corner et al., 2006) uses of natural resources (Angell, 2009; Biradar and Abidi, 2000), potentialities of aquaculture, technical assistance and food security (Meaden and Kapetsky, 2001; Kapetsky, 1994; Kapetsky and Nath, 1997); mapping to assist the aquaculture industry, coastal zone managers and stakeholders in their deliberations about aquaculture potential (Chang et al., 2005), modeling biodiversity to support net pen site selection (Hunter et al, 2006) and climate change (Handisyde et al., 2006).

There have been many applications of GIS for coastal salmonid culture. The Canadian ministry of agriculture fisheries and food (MAFF) developed factors and guidelines for individual site assessment using biophysical capability maps for salmon farming (Caine, 1987). The Norwegian programme, LENKA, was used to model the ability of the marine environment to absorb organic loading from salmon culture and the outcomes were used to assign organic loading capacities to 500 geographically defined zones along the coast (Ibrekk et al., 1993). Ross et al. (1993) developed GIS models for coastal salmonid cage culture site selection using GIS in a small (20 ha) bay in Scotland using a minimum number of spatial variables. Krieger and Mulsow (1990) studied the suitability of finfish in a coastal area in Chile. Perez et al., (2002) developed GIS spatial modelling techniques for particulate waste distribution for Atlantic salmon, *Salmo salar*, raised in cages. This work has been extended by Corner et al., (2006) so that the model is fully integrated into the GIS. Chang et al., (2005) analyzed open ocean aquaculture in the Bay of Fundy, Canada with the objective of assisting the aquaculture industry, coastal zone managers and stakeholders, principally aimed at cage farming of Atlantic salmon. More recently, with the goal of promoting the use of GIS and remote sensing in aquaculture and inland fisheries in developing countries, the FAO Aquaculture Management and Conservation Service has produced reviews and documented the use of GIS for aquaculture with the main aim of maintaining and extending the use of GIS, remote sensing and mapping to improve the sustainability of marine aquaculture (Meaden and Kapetsky, 2001; Kapetsky and Aguilar-Manjarrez, 2007).

## 1.4 Introduction to Enviromental modelling.

Implementation of decision support tools within a GIS is predicated upon the creation of a series of mathematical models. The principal components of a mathematical modelling framework (Thomann, 1982) are shown in Fig 1.3

The two steps enclosed within dashed lines, theoretical construct and numerical specification, constitute the mathematical model distinguishing the simple writing of equations for the model from the task of assigning a set of representative numbers to input and parameters. Following this initial general model specifications are the steps of evaluating model sensitivity, calibration and validation. Sensitivity analysis is used to increase the confidence in the model and its predictions by providing an understanding of how the model response variables respond to change in the inputs, be they data used to calibrate it, model structure, factors used and model independent variables (Saltelli, 2000). Model calibration is the determination of the model parameters and/or structure on basis of measurement and prior knowledge (Janssen and Heuberger, 1995).

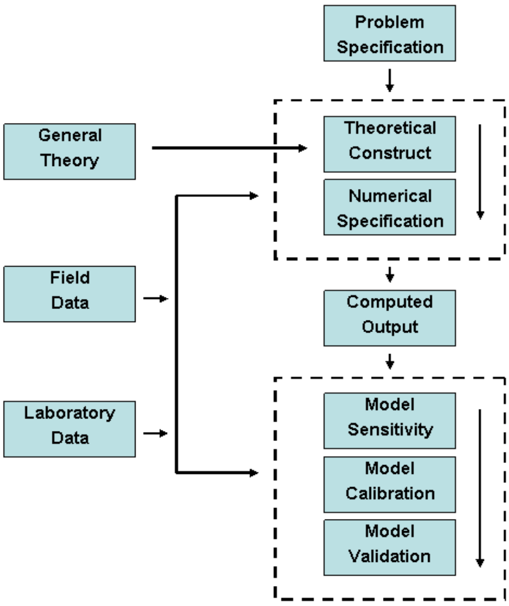

**Figure 1.3. Principal components of mathematical modeling framework. Modified from Thomann (1982).**

The accuracy of a coastal model is closely related to the input provided to it, such as bathymetry and meteorological conditions. The mathematical model developer will apply the best data sources available in order to generate high quality modeled outputs. However, the precision of the model may be limited by the quality of data available and the reliability of the sources. The scientific and technical components of model evaluation are the estimation of consistency between model predicted results and the prevailing scientific theory. A complete model evaluation requires both operational and scientific examination (Wilmott, 1981). The final users will be coastal zone managers and engineers who are concerned with the fitness for purpose of the model and perhaps, most importantly its credibility (Sutherland et al., 2004), and a wide range of stakeholders representing various sectors of industry and the community.

## 1.5 Environmental problems in aquaculture.

Coastal waters are subject to the same seasonal cycles as the open ocean, but the processes are greatly complicated by factors peculiar to the coastal zone, mainly the shallowness, the presence of tidal currents and aspects of the land/water interface (Mann and Lazier, 2006). Coastal ecosystems are characterised by strong seasonality of stratification, nutrient, insolation and topographic factors which play an important role in determining the dynamics of primary production and the vertical flux of organic matter (Wassmann, 1991). The capacity of the marine environment to assimilate waste from aquaculture activities in general is limited by the local hydrodynamic conditions and biological characteristics of the water bodies affected (Gillibrand et al., 2006). Regions of restricted exchange (RRE's) are traditionally preferred sites for human settlement in which aquaculture and their ecosystems and consequent human use may be at environmental risk. Fjordic environments in general are vulnerable ecosystems which readily become subjected to environmental strains because the residence time of anthropogenic derivatives is significantly higher than in the open ocean.

The scale on which aquaculture can impact the environment depends on a combination of factors, including the nature of the pressure, the dispersion rate and pattern and the response time following any impact.

Three impact scales (CSTT, 1994) have been proposed (Fig 1.4):

- Zone A scale is that representing the water volume and sediment area immediately influenced by a fish farm(s).
- Zone B scale is that of the water body and any region of restricted exchange.
- Zone C scale is that of the entire water body that provides the boundary conditions.

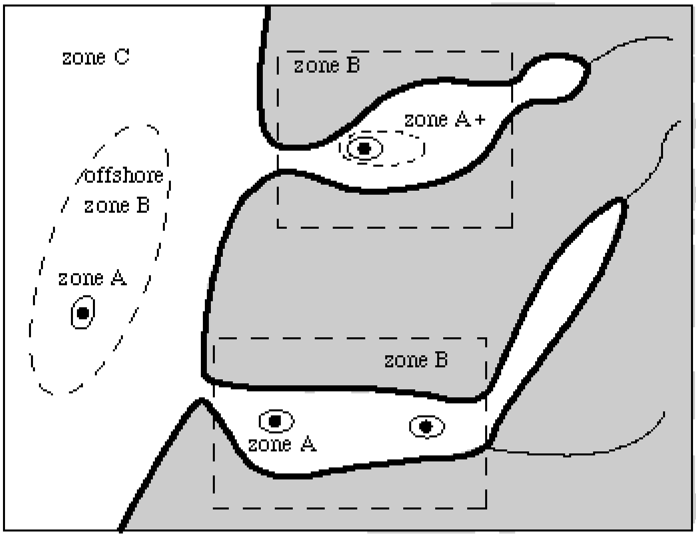

**Figure 1.4 .The scales proposed by the UK Comprehensive studies task team (CSTT, 1994)**

The size of each box in Fig 1.4 is determined by the local dispersion and by the time-scales of critical biochemical processes in relation to the residence time of nutrients within the box. The degree of the nutrient enrichment depends upon farm species, food quantity and quality, management, water currents and depth (Beveridge, 2004).

Carroll (2003) suggested that the potential sensitivity to impacts from fish farming is based on the hydrodynamism at the site. The term Ecohydrodynamics in aquaculture has been coined by Tett (2008) to describe the physical conditions at a site and in the water body and the chemical and biological conditions that would naturally occur under such conditions. The sensitivity to waste of the water or sea bed at a particular farm site depends on the Ecohydrodynamic conditions at and around that site and the spatial and temporal scale. The term sensitivity (SAMS, 2004) is used here to mean the extent to which a given amount of aquaculture will result in an 'impact' on the ecosystem in which the aquaculture takes place.

The extent to which a proposed site is sensitive to pressures from the wastes from farmed fin-fish depends on key parameters such as minimum current speed, depth, residence time (SAMS, 2004). Descriptions of hydrodynamic processes that dominate water exchange were used to predict the environmental impact of waste and nutrient, and to develop a carrying capacity model based on the potential for nutrient enrichment from estimated numbers and sizes of salmon held in cages (Strain et al., 1995).

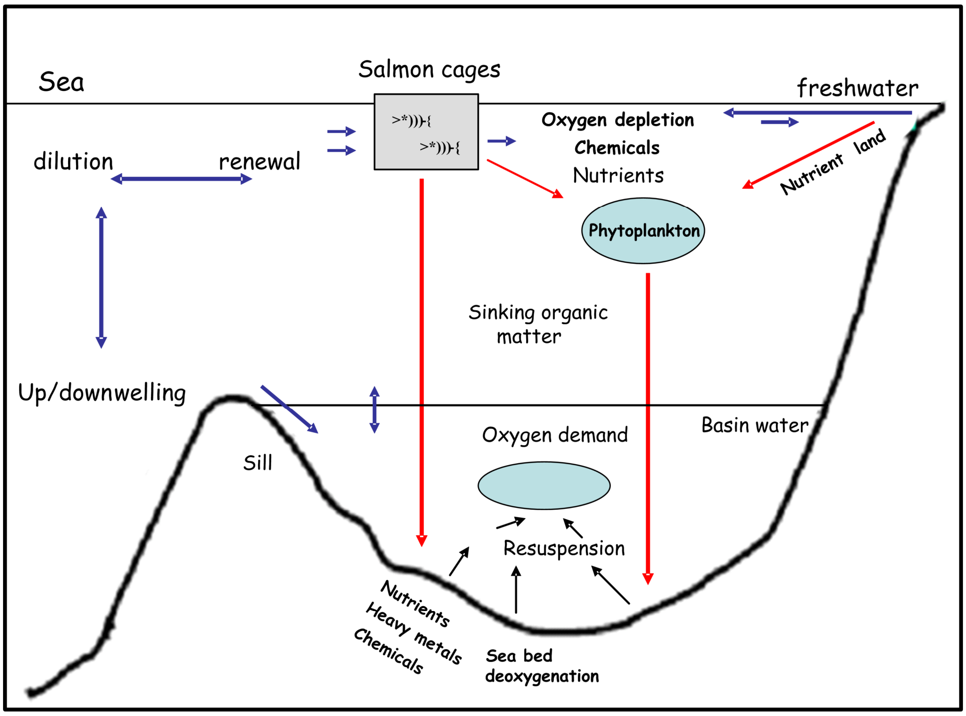

**Figure 1.5. Effects of aquaculture in a region of restricted exchange.**

The potential effects of farming fish in cages (Fig 1.5) on the marine environment coming from uneaten food and excreted material may lead to organic enrichment of the sediments below the cages, and hypernutrification and oxygen depletion in the water column (e.g. Gillibrand et al., 1996  Silvert, 1992;  Brown *et al*., 1987; Pearson and Gowen, 1990). Wildish et al., (2004), suggest how in the near field this waste may be transported and dispersed from the fish farm to the local coastal environment by the action of all types of water movements in the immediate vicinity of the cages.

Hargrave (2003) considered that the environmetal impacts of fin fish aquaculture may be classified into three types of broad-scale distant changes from farm sites: eutrophication, sedimentation and effects on the food web. Beveridge (2004) also suggests that there will be increases in nitrogen and phosphorous compounds in the overlying waters. The difficulty in interpreting environmental affects is the difficulty in relating the occurrence of harmful algal blooms due a nutrient enrichment from finfish farms. In addition, local hydrographic conditions that characterize the farm area may influence the recovery rates in quiescent and low hydrodynamically energetic areas, the recovery may take much longer than in more energetic areas (Pearson and Black, 2001).

## 1.6 Coastal models in aquaculture.

Numerical circulation models, based on a set of mathematical equations that govern fluid motion, provide a practical solution to the problem of understanding coastal mixing in aquaculture areas (Wildish et al., 2004). “Coastal modeling” is defined as the modeling of coastal and shelf seas excluding specialist topics such as beach processes or river models that do not include a portion of the adjacent shelf sea (Jones, 2002). These coastal models can be applied to many different ecological and environmental problems by using a range of model configurations and forcing (wind and tides mainly) in a depth-averaged two-dimensional (2-Dimensions) application or in a full three-dimensional (3-Dimensions) form. 3D models would be extremely useful not only for aquaculture but also for a wide range of research and management applications (Andréfout et al., 2006).

The main potential and recommendations for such models in aquaculture could be as an indicator, as a descriptor of well understood physical processes, as a tool for guiding best practices in development and regulation, or as a cost effective alternative to extensive field studies. They may also provide fast predictions for potential impacts for different aquaculture scenarios (Henderson et al., 2001).

A number of authors have addressed the questions of circulation, flushing time and oxygen depletion (Greenberg et al., 2005; Trites and Petrie, 1995; Brooks and Churchill, 1991), nutrient and pesticide dispersion (Falconer and Hartnett, 1993), sea lice dispersion (Murray and Gillibrand, 2006) and waste dispersion in finfish aquaculture (Dudley et al., 2000). Taboada et al. (1998) studied the residual circulation in the Ria of Vigo, an important area of mussel culture. The Hong Kong bay area has been fully modeled (Lee et al., 1991; Lee and Arega, 1999; Lee et al., 2003) and it is clear that marine fish farms in the area are located in eutrophic coastal waters, often with severe dissolved oxygen depletion, algal blooms and red tides. The models provided predictions of algal biomass, dissolve oxygen and nutrients.

Andréfout et al. (2006) described the state of the art in designing well constrained 3D models, useful for aquaculture applications and estimated the cost of implementing, calibrating and validating a numerical model for an semi-enclosed atoll lagoon for mollusc aquaculture. Duarte et al. (2003) implemented a 2D hydrodynamic model coupled with a physical-biogeochemical model in an area with extensive polyculture, and used it to estimate the environmental carrying capacity for polyculture of scallops and oyster. Ferreira et al. (2007) used a 3D model to simulate tidal, wind and ocean currents in the studies areas to develop dynamic ecosystem-level carrying capacities for some Irish Sea Loughs for shellfish culture. Skogen et al. (2009) coupled a physical chemical and biological 3D ocean model and modelled a fjord and concluded that there was a small increment in the primary production and no impact in the oxygen level form fish farming in the study area.

## 1.7 Fuzzy logic in environmental modeling.

Mathematical models in general combine a variety of inputs and procedures to derive an output and are widely used, particularly in environmental modeling. Although such model outputs represent a single point in time and typically combine multiple inputs into a single output, the results are often of great value as predictors or indicators of environmental problems (Longley et al., 2005). Ambiguity may also arise in the conception and construction of these indicators and in environmental classification.

A particular problem arises where the boundary of a piece of information is not clear-cut and there is no single quantitative value which can be assigned in that area. For example, concepts such as young, small, good, low or medium are relative concepts and have no clean boundary. For some people, age 20 is young, while for others, age 35 is still young. Age 5 years old is definitely young and age 70 is definitely not young, however, age 35 has different possibilities depending upon the context in which it is being considered. The representation of this kind of information is based on the concept of “fuzzy” set theory (Zadeh, 1965) in which the use of fuzzy sets relaxes the definition of a boundary and admits intermediate values of class membership.

Unlike classical or Boolean set theory where one deals with objects whose membership to a set can be clearly described, viz:

$$\mu_A : \mathbf{U} \rightarrow \{\mathbf{0,1}\} \quad \text{Eq (1)}$$

where a number $\mu_A$ (x) is associated with the values {0,1}, 1 or 0 with each element x of U, in fuzzy set theory, membership of an element to a set can be partial, i.e., an element belongs to a set with a certain grade (possibility) of membership.

More formally, a fuzzy set A in a universe of discourse U is characterized by a membership function:

$$\mu_A : \mathbf{U} \rightarrow [\mathbf{0,1}] \quad \text{Eq (2)}$$

where a number $\mu_A$ (x) in the interval [0,1] is associated with each element x of U. This numerical value represents the grade of membership of x in the fuzzy set A. For example, the fuzzy term young might be defined by the fuzzy set in Table 1.1.

Table 1.1.Example of young membership grade.

| **Age** | **Grade of Membership** |
|---|---|
| **20** | **1.0** |
| **30** | **0.8** |
| **35** | **0.4** |
| **40** | **0.0** |

Regarding equation (1), one can write

$\mu_{young}$ (20) = 1, $\mu_{young}$ (35) = 0.4, ... , $\mu_{young}$ (40) = 0

Grade of membership values constitute a possibility distribution of the term young. The table can also be shown graphically (Fig 1.6)

**Figure 1.6. Possibility distribution of young.**

Relative water temperatures such as cold, warm and hot can also be represented as fuzzy sets and Fig 1.7 shows how any temperature between 0 to 40 $^{o}$C can be given numerical values as members of the cold, warm and hot fuzzy sets.

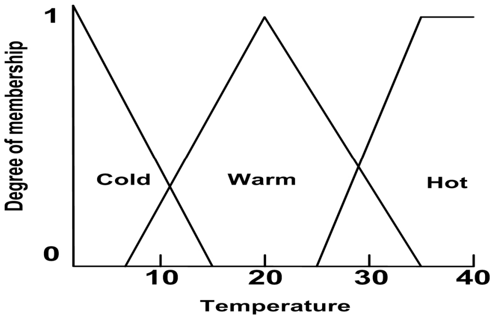

**Figure 1.7. Cold warm and hot as fuzzy set from Openshaw and Openshaw (1997)**

The important point is that linguistic concepts, terms and classes such as young, cold and hot are being cast into a form that can be represented and incorporated in computer software for which there is also mathematical basis for handling the varying degrees of imprecision that is present (Openshaw and Openshaw, 1997). The fuzzy sets are defined by two main components; membership functions and rule bases.

The membership function is a mathematical function which defines the degree of an element’s membership in a fuzzy set and is denoted by a membership value between 0 and 1. The shapes of the fuzzy sets are defined by these membership functions which are a representation of a linguistic variable to a fuzzy set as a matter of degree. There are five kinds of functions that are commonly used. These are triangular, trapezoidal, bell-shaped (Fig 1.8) and S function and exponential functions.

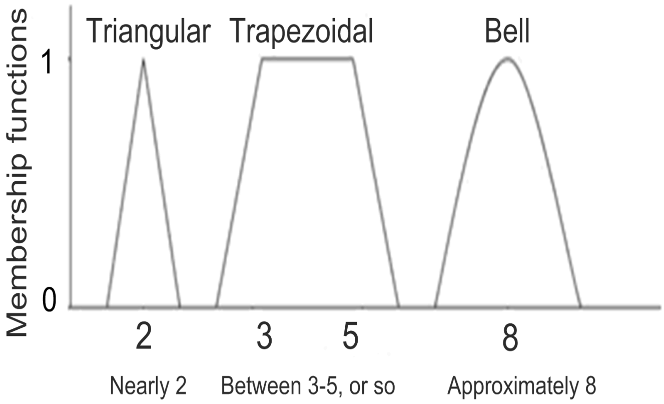

**Figure 1.8. Three types of fuzzy memberships.**

A fuzzy model is a series of IF-THEN rules that when processed as fuzzy set connects a set of inputs to a set of outputs. It is a means of giving a computer the capability of reasoning with fuzzy numbers in the form of fuzzy rules.

The knowledge or intelligence comes from associating fuzzy set events for example “If the temperature is high and the oxygen concentration is low then high vulnerability “,in this association of two fuzzy events the rules reflect any knowledge about the systems being modeled. Fuzzy logic provides yet another framework for redoing, rethinking and re-expressing most of the conventional modeling and statistical applications of geography (Openshaw and Openshaw, 1997). GIS and spatial databases are suited for fuzziness, because of the uncertainty and vagueness inherent in the assimilation, errors, storage, representation and final visualization of spatial data (Morris and Jankowski, 2009), and due to the fact that there are many geographic objects with uncertain boundaries and fuzzyness is a natural way to represent this uncertainty, vagueness and inaccuracy (Burrough, 1986). In many real world problems and situations, the spatial extent of geographical entities are uncertain and vague. In such cases features may be represented using fuzzy sets through the construction of “fuzzy geographical entities” (Fonte and Lodwick, 2006).

Morris and Petry (1998) and Counclelis (1996) provide many examples of how fuzziness can exist in the objects within a GIS. In the environmental modelling context the most important are the boundaries, temporality and resolution and missing data. GIS research can be complex and it is vital for the viability of GIS technology to provide for approaches that deal with inaccuracy and uncertainty (Goodchild and Gopal, 1990; Morris and Jankowski, 2009). Openshaw and Openshaw (1997) identify several types of systems and GIS problems where adopting a fuzzy approach may be necessary or beneficial in different situations. These include complex systems that are difficult or impossible to model as they have no firm mathematical basis, systems for which there is descriptive and theoretical knowledge expressed only in a linguistic form, situations in which when there is little or no training data from which to estimate anything but there is sufficient knowledge to specify a linguistic model that is be used to make predictions, and when human reasoning, human perception or human decision-making are inextricably involved. The authors also noticed that the Fuzzy logic based modelling offers a number of potential benefits: It provides a linguistic, non numerical, non-mathematical and non statistical based approach to modelling complex systems and robustness because of its ability to handle imprecision.

Finally fuzzy logic may be combined with other areas such as neural networks and genetic algorithms, providing a basis for a new generation of advanced intelligent hybrid Neuro-fuzzy systems. Neuro- Fuzzy systems are fuzzy systems that are trained by a learning algorithm (normally a neural network theory), or enhanced by learning from examples, training data sets, (Nauck and Kruse, 1999). They can be used to develop new approaches and solve specific existing geographical and environmental problems. They have strong potential in the combination of technologies such as hydrodynamic models, GIS and intelligent systems and, while computationally challenging, their use has been facilitated by the new advancements in computer technologies.

## 1.8 Objectives.

1. The main objective of this study is to develop a model to predict coastal environmental vulnerability for salmon marine cage aquaculture.
2. The study focuses upon the description of the physical processes, including the circulation patterns, dispersion and transport processes and the water renewal in Mulroy Bay.
3. A specific objective is the development of an environmental spatial model that can be applied in coastal areas and which is intended to facilitate policy decisions, taking into account the intrinsic characteristics of the target area.
4. Finally, a soft computing application will be developed for classification of GIS cells and further evaluation and analysis of the quality of the classification achieved.

Mulroy Bay is an Irish fjard, an area of restricted water exchange in which there are several important aquaculture activities. These activities may increase the risk of environmental problems intensified by the poor water exchange and hence a rational and sustainable aquaculture management system is needed.

A 3D hydrodynamic model coupled to a particle-tracking model is applied the water circulation patterns, dispersion processes and flushing and residence time in Mulroy Bay. The hydrodynamic model is intended to provide spatial and temporal information on circulation and renewal time and help to determine the influence of winds on circulation patterns. This model can also be used to study the effects of mean current speed, quiescent water periods, stratification and bulk water circulation in Mulroy Bay. These spatial models developed can also be used to identify areas for appropriate site selection for salmon aquaculture and a Langangrian method was used to simulate discharges from finfish cages to show the behaviour of waste in terms of water circulation and water exchange (Chapters 3 and 4).

Neuro-fuzzy techniques were used in a GIS to predict coastal vulnerability for marine cage aquaculture (Chapter 5). Finally, a Neuro-fuzzy classifier was developed for supervised and hard classification of GIS cells in the coastal environmental vulnerability using minimal training sets and further evaluation and analysis of the quality of the classification achieved (Chapter 6).

The chapters in this thesis take the form of series of draft manuscripts readied for publication. The contribution of Juan Moreno to all of them includes the totality of the field sampling, data collection, laboratory work, statistical analyses and writing up the manuscripts. All other authors provide assistance with the experiment design, guidance and proof reading for all of the chapters.

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# Chapter 2 Study area.

## 2.1 Topography.

Mulroy Bay is an extremely sheltered, narrow inlet situated on the north coast of County Donegal Ireland (Long 7° 45” , Lat 55° 15”) (Fig 2.1). It is bounded on the west by the Rosguill Peninsula and on the east by Fanad Peninsula. It is a convoluted and complex environment, extending inland for about 19 km, with a range of hydrodynamic conditions. The long narrow embayment, covers approximately $35km^2$ and the catchment of the bay extends to $136km^2$. The bay is a glacial fjard ranging in depth from 0 to 51m and is the most convoluted of the marine inlets in north-west Ireland. The bay is divided into four main areas: the Outer Bay, Northwater, Broadwater and the Narrows (Fig 2.1). The Narrows is further sub-divided into three sections each approximately 100-150 m wide, known as first, second and third Narrows. In addition to aquaculture, marine activities in the area include sea angling, diving, boat building and repair.

## 2.2 Geology and Land Use.

The surrounding geology, summarized by Parkes (1958), is principally a metamorphic bedrock of quartzite, schist, crystalline limestone, and gneiss, with intrusive granite at the mouth. The beaches range from boulders to stones, sand or sand and mud with rock outcrops. The adjacent soils are mainly brown and peaty podzols and tend to be well draining and are suitable for arable land. The land is used for a mixture of improved grazing, both broadleaf and deciduous forestry, intermingled with moor, heath and bog, The main farming practices are grazing and beef production. Principal freshwater inputs are the Burnside, Loughkeel Burn, the Bunlin, and the Big Burn. The population of the catchment is approximately 10 to12.000 inhabitants with the main settlements being Carrickart (Pop. 828), Milford (Pop. 1,385), and Carrowkeel (Pop. 200).

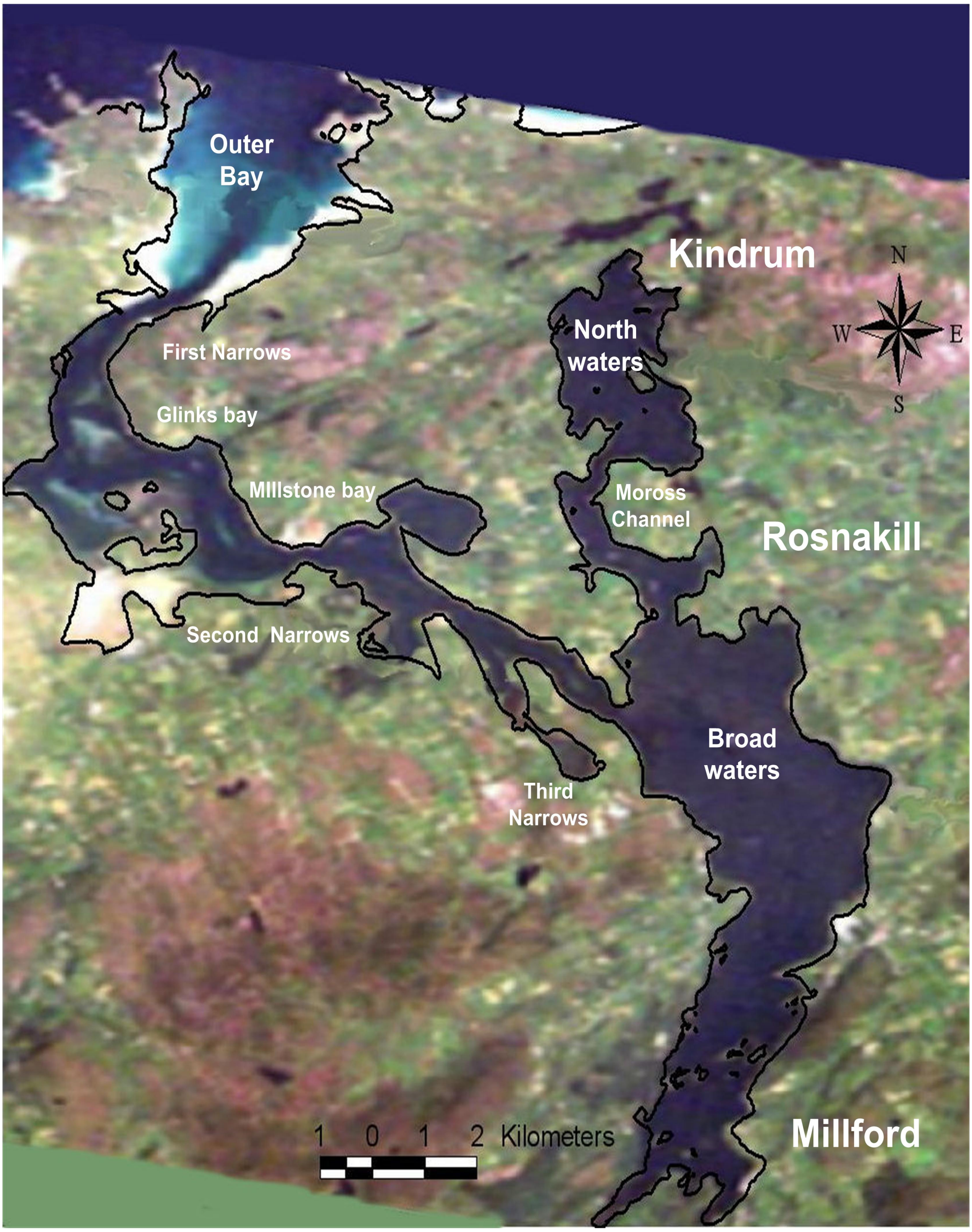

**Figure 2.1. Landsat image of Mulroy Bay**

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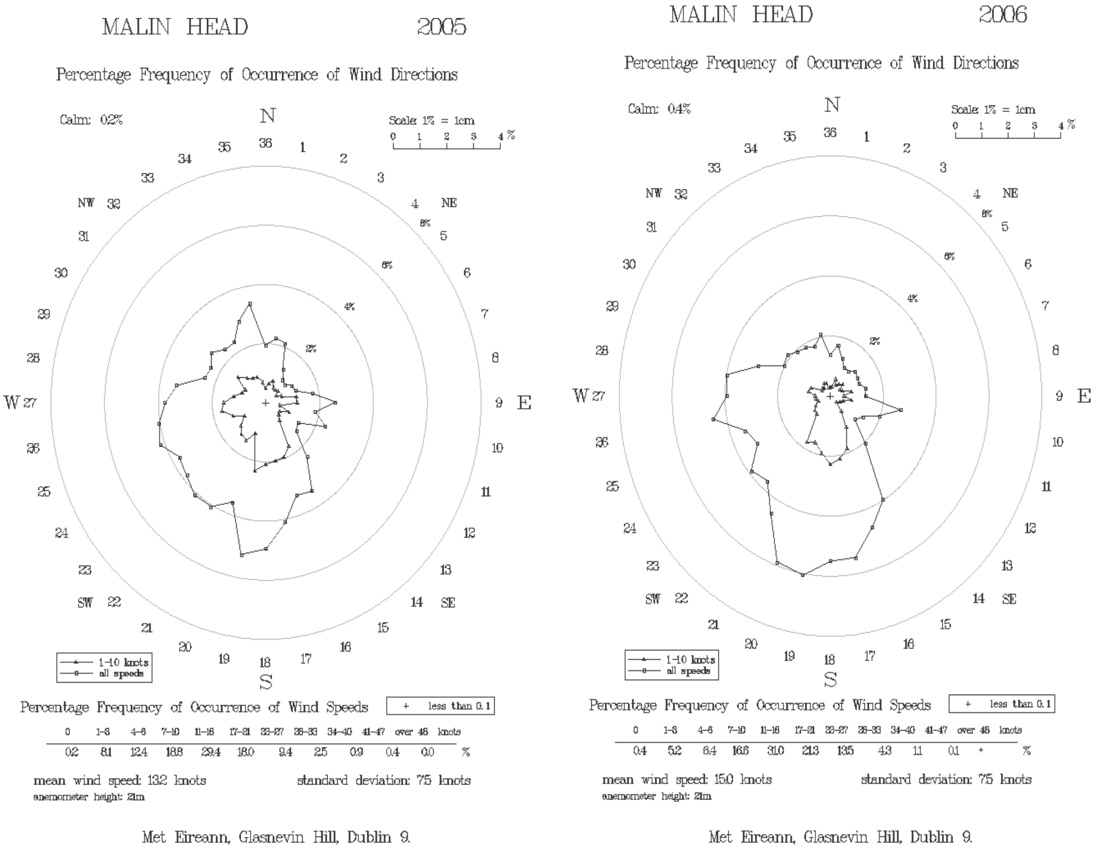
## 2.3 Meteorology.

The nearest meteorological weather station is located in Malin Head, 35 km north east of Mulroy Bay. The winds in 2005 had a mean velocity of 6.8 m/s and were predominantly from a south-westerly direction; 225º gridN (Met Eireann Institute) (Fig. 2.2). The average monthly air temperature recorded at Malin Head was 10.4º C with the highest monthly average temperatures in August. The average annual rainfall of 1245 mm was recorded at in Carrowkeel on the shores of in Mulroy Bay, with a mean of relative humidity of 89%.



| 0 | 1–3 | 4–6 | 7–10 | 11–16 | 17–21 | 22–27 | 28–33 | 34–40 | 41–47 | over 48 | knots |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.2 | 8.1 | 12.4 | 18.8 | 29.4 | 18.0 | 9.4 | 2.5 | 0.9 | 0.4 | 0.0 | % |

mean wind speed: 13.2 knots standard deviation: 7.5 knots
anemometer height: 21m

Met Eireann, Glasnevin Hill, Dublin 9.

| 0 | 1–3 | 4–6 | 7–10 | 11–16 | 17–21 | 22–27 | 28–33 | 34–40 | 41–47 | over 48 | knots |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.4 | 5.2 | 6.4 | 16.6 | 31.0 | 21.3 | 13.5 | 4.3 | 1.1 | 0.1 | + | % |

mean wind speed: 15.0 knots standard deviation: 7.5 knots
anemometer height: 21m

Met Eireann, Glasnevin Hill, Dublin 9.

**Figure 2.2. Percentage frequency of occurrence of wind direction and speed in 2005 and 2006.**

## 2.4 Biodiversity.

There is little published work on the physical environment, fauna, flora and biotopes of Mulroy Bay. Parkes (1958) studied the intertidal algae and there is some data on species of fishes and molluscs of the area (Fahy ,1983; Minchin, 1996, 1981, Nunn, 1996). Mulroy Bay contains of two habitats listed in Annex I of the EU Habitats Directive – reefs and large shallow inlets and bays and is a special area of conservation (SAC).

The site contains a good range of different sediment and habitat types and include coarse sand in which is found two species of the free-living red calcareous algae called maerl *Lithothamnion coalloides* and *Phymatolithon calcareum.* Both are listed in annex V of the EU habitats directive (Directive 92/43/EEC). The variety of different habitats within the site is reflected in the high number of communities found in the bay and the high species diversity. Rare species found in Mulroy Bay include Couches goby *Gobius couchi*, the file shell *Limaria hians*, the anthozoan *Paraerythropodium coralloides* and the hydroid *Halecium muricatum.*

The shores of Mulroy Bay are a mixture of rocks, boulder, cobbles and gravel which support a community typically comprising the common brown alga *Ascophyllum nodosum.* The shallow water reefs and pools exposed to wave action are characterised by the brown seaweeds and support a range of invertebrate epifauna such as bryozoans, hydroids and ascidians and epiflora.

The intertidal areas support the brown seaweeds *Halidrys siliquosa* and kelp forests of *Laminaria hyperborea,* the red alga *Dudresnaya verticillata* and the reddish orange encrusting soft sponge *Esperiopsis fucorum.*

The seagrass *Zostera marina* and *Zostera noltii* (Fig 2.3) is found in inner Mulroy Bay and this community normally harbours the sea cucumber *Leptosynapta inhaerns*.

Fifty-nine species of fish were found in a survey by Minching 1996, with five species being seasonal or occasional: *Clupea harengus*, *Clupea spratus*, *Belone belone, Scomber scombrus* and *Chelon labrosus*. In common with the native salmonids such as *Salmo trutta*, *Salmo salar* and the introduced *Onchorhynchus mykiss* also occurs.

Species classed as sensitive to aquaculture (Hunter et al 2006) include *Phymatolithon calcareum, Ascophyllum nodosum, Zostera marina, Zostera noltiir, Lithothamnion coralloides*, *Ostrea edulis,* and *Nucella lapillus.*

**Figure 2.3 . *Zostera marina* and *C. melops*. (Biomar CD-ROM from Picton and Costello, 1998 )**

The otter, *Lutra lutra*, a species listed in Annex II of the EU Habitats Directive, frequents the site and Mulroy bay is one of the fourteen major European breeding sites for the harbour or common seal, *Phoca vitulina* listed in the Appendix III of the Berne convention and annexes II and IV of the Habitats Directive.

The Bay also supports significant numbers of wintering birds, with mute swan present in nationally important numbers and several species (brent goose *Branta bernicla,* shelduck *Tadorna tadorna*, wigeon *Anas penelope*, teal *Annas crecca*, red-breasted merganser *Mergus serrator*, oystercatcher *Haematopus ostralegus* and dunlin *Calidris alpina* ) recorded in regionally important numbers.

## 2.5 Water Quality.

Water quality has been measured throughout Mulroy Bay since the Institute of Aquaculture (University of Stirling) began its annual monitoring surveys in 1986. Both physical and chemical parameters have been monitored, including temperature, dissolved oxygen (D.O.), pH, salinity, nitrite, nitrate, ammonia, dissolved reactive phosphorus (DRP) and chlorophyll-a at various locations in the Bay. These parameters have been assessed annually at 8 to 12 sites at the same time each year (i.e. during the final week of July), thus allowing comparisons to be made between survey results from different years. The findings have been summarized by Telfer and Robinson (2003).

Water temperatures were found to be consistently lowest at the two outermost sample stations in Mulroy Bay, located near to its mouth while the innermost stations were consistently warmer. Similarly, temperatures near the seabed were generally lower than those in the surface waters, as is usually the case.

Salinity values were very similar at the surface and seabed at each sample station, with little variation occurring between sample years. Values generally ranged between 31 and 36 psu.

Data collected indicated that little overall variation occurred in D.O. between 1986 and 2000, with levels varying annually at the surface between a minimum of 6.3 mg / l and 10 mg / l. Deep water D.O. varied between a minimum of 2.4 mg/l to a maximum of 9.8 mg/l.

pH values were consistent between the surface and seabed at each sample station, with little overall variation between years. Values ranged from 8.33 to 8.53 at the surface, and from 8.31 to 8.52 at the seabed.

The trends in ammonia were found to be very similar in both surface and deep waters, with large variations in concentrations being recorded between sampling stations and between sampling years. The nitrate levels showed no overall trends either increasing or decreasing over the 14 years. The nitrate concentrations varied between sample years and sites, but were generally low in Mulroy Bay. C-Mar (2000) found that nitrate levels tended to fluctuate throughout the year. In general, dissolved reactive phosphorus levels increased and fell between the studied years, showing small signs of an overall trend. Considerable fluctuations in phosphate concentrations were also found by C-Mar (2000) both throughout the year. Values for biochemical oxygen demand measured by C-Mar (2000) showed that water quality within the fjord was acceptable at present aquaculture production levels.

Telfer and Robinson (2003) concluded that there was no indication of a general augmentation in nutrient levels within the area over the several years studied, although they did emphasize that concentrations elevated occasionally due to reduced water exchange rates in the inner parts of the bay.

## 2.6 Current and future developments and potential effects on water quality.

The primary development pressures in the area are for housing, both for the local population and for houses as holiday homes and civil engineering projects.

**Figure 2.4. New bridge in the second narrow area in Mulroy Bay.**

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A new bridge construction (Fig 2.4) has temporarily increased environmental pressure in this area and specially in the large salmon production area held in the study area .The bridge is located at Boathill Bay, usually referred to as The Second Narrows, and will be 342m in length, and is the largest bridge built  in Donegal County. The construction of the bridge began in March 2007 and it will connect the Rosguill and Fanad Peninsulas. A real time monitoring was used a 24hour real time monitoring buoys in four locations of the bay. The sensors measured turbidity, dissolved oxygen, chlorophyll, salinity and current velocity. Monitoring carried at 15 minute intervals.

The monitoring continued throughout the construction of the Mulroy Bay Bridge until the bridge was completed and operational. The new bridge in was officially opened on 15th May, 2009 without environmental problems reported.

In accordance with the monitoring requirements of Directive 79/923/EEC, on the quality required of shellfish waters, and Directive 91/492/EEC, dedicated shellfish monitoring data has been collated and compared with shellfish water quality parameter mandatory and guideline values outlined in Annex I of the Shellfish Waters Directive ( Directive 2006/113/EC). Data are available for several water samples which were taken between 2004 and 2008 and 6 biota samples which were taken between 2004 and 2008 (Department of the Environment, Heritage and Local Government, 2008b). During the study years the mandatory values for copper and nickel, lead, zinc and faecal coliforms were breached. The shellfish guideline standards were never exceeded during the study period (Department of the Environment, Heritage and Local Government, 2008b).

The Water Framework Directive ( Directive 2000/60/EC) status of the coastal water bodies, within Mulroy Bay was either ‘high’ and therefore satisfactory or ‘moderate’ and therefore unsatisfactory, reflecting the results of zinc in some of the pollutant sampling. Two rivers, Burnside and Bunlin, discharge into the area and are both classified as ‘poor’ and therefore unsatisfactory reflecting issues with the macro invertebrates. Shellfish flesh classifications (carried out under the European Communities (1996). Live Bivalve Molluscs, Health Conditions for Production and Placing on the Market Regulations, 1996 (S.I. No. 147 of 1996) indicate faecal contamination in shellfish flesh.

The population of these Electoral Districts is 10,000. Of these, it is estimated that is only 76% are served by sewage collection systems (Department of the Environment, Heritage and Local Government, 2008a,b). The key and potential secondary pressures identified those most likely and possibly affecting the water are: A) On-site waste water treatment plants, where the risk to surface and ground waters from pathogens and nutrients is also high throughout the catchment. There is also the possibility of inadequate percolation and located in the coastal areas.  B) Urban waste water treatment plants. One such plant situated within the catchment has been designated as ‘at risk’ due to inadequate treatment capacity resulting in exceeding the shellfish water quality parameters. C) Agriculture. This catchment is predominantly farmed land (45%) and the prevalence of wet soil types in the catchment means that there is a risk of agricultural runoff to the coastal areas (Department of the Environment, Heritage and Local Government, 2008b).

Tributyltin (TBT) was used in Ireland as an antifoulant on shipping, small boats and yachts and on nets of salmon cages. In Mulroy Bay the principal source of TBT was from salmon farms. From 1981-1985 TBT was used within the Bay as an antifoulant on salmon cages and associated with a decline in the population of *Lima hians.* (Minchin, 1995; Minchin, 2003).  The native scallop settlements showed a decline in intensity in 1982 followed by three years of settlement failure. In addition, Pacific oysters, *Crassostrea gigas*, ongrown in several areas of the bay in 1985, developed shell thickening. In 1994 the Mulroy Bay population had recovered to 1980 levels, and Minchin (2003) showed that there were minimal levels of TBT contamination in 2000, which are unlikely to have ecological effects on mollusc culture or fisheries in the area (Minchin, 2003).

## 2.7 Aquaculture in Mulroy Bay.

Mulroy Bay was designated as a mariculture site in 1981 under council directive 79/923/EC for shellfish culture, although salmonid culture started in 1979.

Aquaculture in Mulroy Bay is intensive (Fig 2.5), with up to 16 operators currently licensed for Mussel, *Mytilus edulis* (19 licences with 0.6 $km^2$), oyster *Crassostrea gigas* (9 licences with 0.34 $km^2$), clams *Tapes semidecussata* (3 licences with 0.1 $km^2$), scallops P*ecten maximus* (30 licences with 5.04 $km^2$), abalone *Haliotis tuberculata* (2 licences with 0.9 $km^2$) and atlantic salmon *Salmo salar* production. The total value for aquaculture production within Mulroy Bay for 2001 was approximately £8m, with up to 243 people employed on a fulltime, part time or casual basis. Oysters are cultured on trestles in the intertidal zone while mussels are suspended on ropes from floating barrel rafts, and the scallops are grown on bottom trays relying on natural recruitment processes. Abalone and clams are not currently in production within the bay.

Dramatic increases have occurred in shellfish production, with figures rising from 250 tonnes per annum to approximately 1000 tonnes per annum between 1994 and 1999, (C-Mar, 2000). In 2004, 600 tonnes of bottom mussels were harvested from the area. Between 2000 and 2004, average tonnage of Pacific oysters was 14 tonnes. Native oyster production between 2003 and 2004 averaged 3 tonnes per annum. Between 2000 and 2004, the average rope mussel harvest was approximately 586 tonnes. Mature scallops landed for the same period were 45 tonnes per annum.

The licensed area is classified as Class B for Mussels meaning that shellfish may be placed on the market for human consumption only after treatment in a purification centre or after re-laying so as to meet the health standards for live bivalve molluscs laid down in the EC Regulation on food safety (Regulation (EC) No 853/2004).

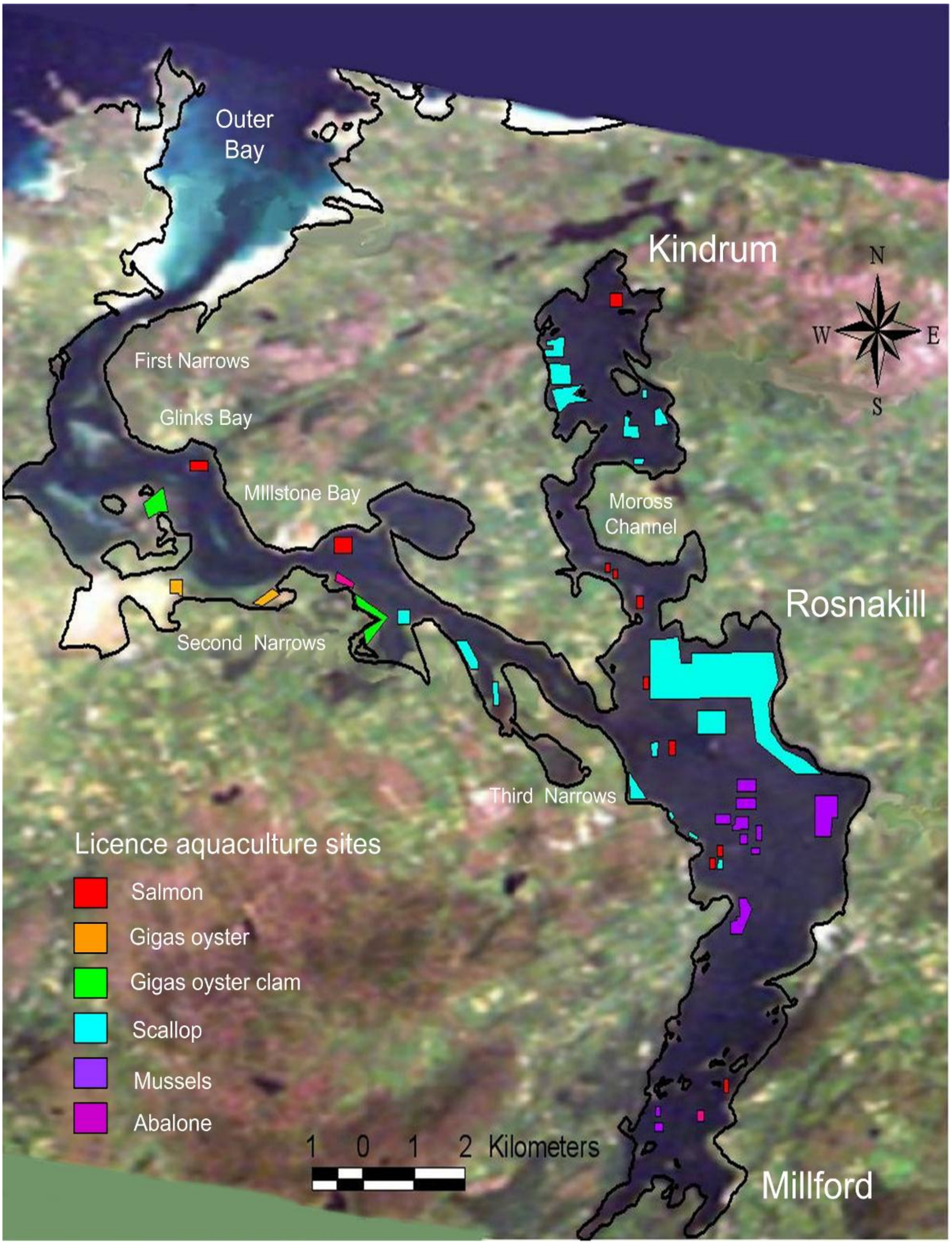

**Figure 2.5 . Areas licensed for aquaculture in Mulroy Bay (from County Donegal Development Plan 2005).**

Mulroy Bay is classified ‘A’ for oysters in accordance with the European Communities (1996) .However, within the designated area this is a seasonal classification and it reverts to Classification B. This indicates that there is faecal contamination in this shellfish area.

The salmon operation (Fig 2.6) is owned by Marine Harvest Ireland, which is part of the largest salmon farming and marketing group in the world, with operations in Scotland, Chile, Ireland, Norway and Canada and sales offices in all the world’s major outlets. Marine Harvest Ireland represents about 12 % of the production in Ireland and currently employs 190 staff across its operations and a number of subcontracted businesses. Atlantic salmon production within Mulroy Bay and the adjacent Lough Swilly is approximately 3500 tonnes per annum (Bermingham and Mulcahy, 2007)

**Figure 2.6 . Mulroy Bay. Looking across Boat Bay towards the salmon fishery.**

Mulroy Bay, had suffered elevated lice levels occasionally during the critical spring period, (O'Donohoe et al., 2004). The amoebic gill disease (AGD), described as amoebic-associated gill pathology, has been experienced annually since 1996 with mortalities reaching 60% in site. This disease is associated with compromised marine environmental factors, principally ammonium, nitrite and chlorophyll (Bermingham and Mulcahy, 2007). Donnelly and Reynolds (1994) reported the occurrence of the ectoparasitic copepod *Leposophilus labrei* on the wrasse, *C. melops*. This fish has been used to control biologically infestation of sea lice (Copepoda: Caligidae) in farmed sea salmon in Ireland (Costello, 1994).

Telfer and Robinson (2003) found that the environmental quality within Mulroy Bay was acceptable, although localized impacts were found near to fish farms. Two scientific methods to assess this were used; the calculation of food availability for sustainability of shellfish culture, developed by Carver and Mallet (1990) and, the oxygen budget estimation of the system to ensure the environmental sustainability of both finfish and shellfish farming at current levels. However, C-Mar, (2000) concluded that the capacity of the environment to support aquaculture indicated that while present production levels are within this capacity they may be approaching the upper limits. An Irish national program “Co-ordinated Local Aquaculture Management systems” (CLAMS) has been developed at local level to manage the development of aquaculture in coastal areas and Mulroy Bay is included in the program. The main objectives are to improve environmental compliance, product quality and consumer confidence.

## 2.8 The Mulroy Bay spatial database.

The data used for model construction came from one of four sources. A range of parameters of hydrography, water quality and sedimentology have been measured throughout Mulroy Bay since the Institute of Aquaculture (University of Stirling) began its annual monitoring surveys in 1986. These data were used as a basis for the present study but were supplemented by field campaigns designed to update and expand the datasets necessary for this study (Fig 2.7). Further datasets were obtained either from the Internet or by direct purchase from relevant government agencies. All data used for spatial modeling was rasterised to 50 m resolution.

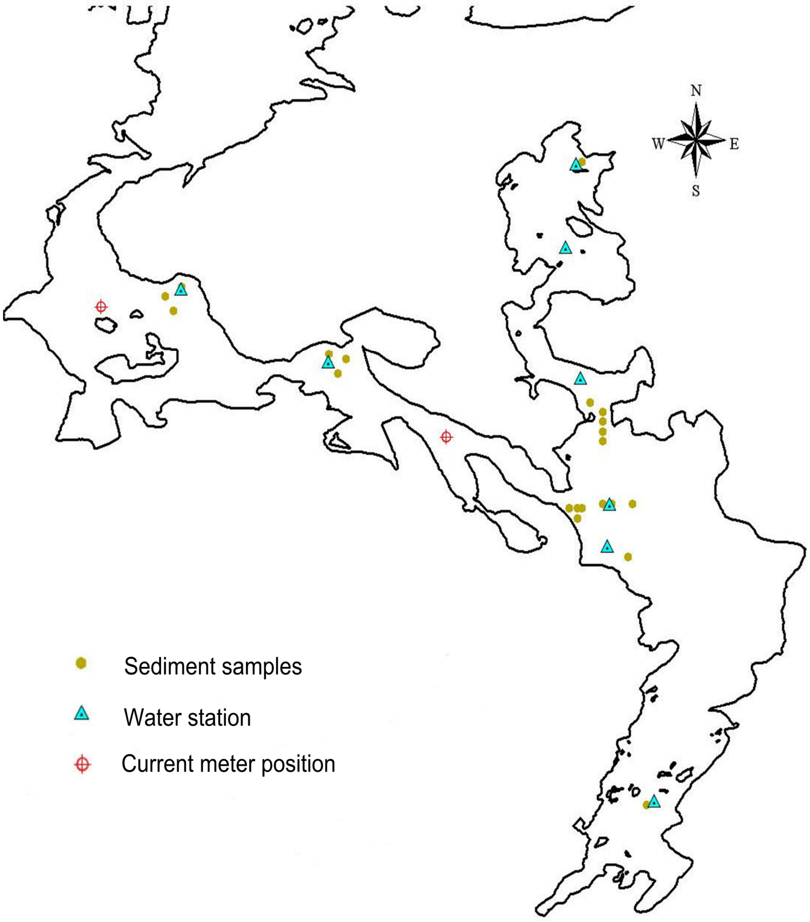

**Figure 2.7. Locations of sediments, water and current speed measurements.**

### 2.8.1 Bathymetry.

A bathymetric model was obtained by digitizing from Admiralty Chart (SNC 2699) to produce initial vector data followed by interpolation to a 50 m grid resolution. A digital elevation model in 3D was produced (Fig 2.8).

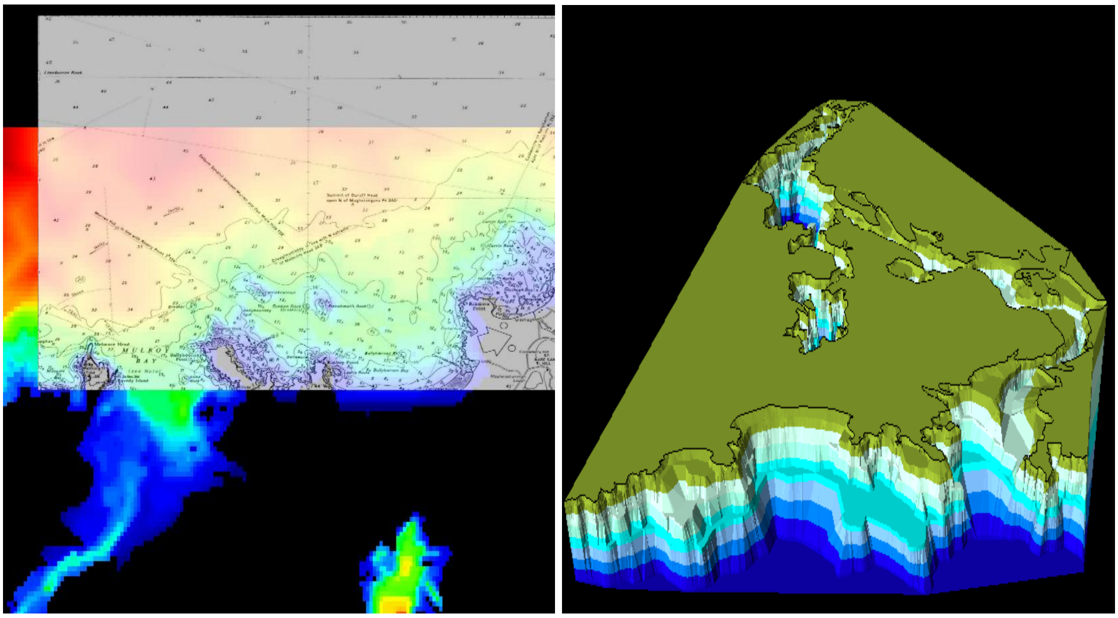

**Figure 2.8. Admiralty Chart (SNC 2699) and the bathymetry raster layer overlaid onto a digital elevation model in 3D GIS of Mulroy Bay**

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### 2.8.2 Hydrographic data.

Hydrographic measurements were taken from two stations within Mulroy Bay (Fig. 8). Valeport BFM 308 Direct Recording current meters (Fig 2.9) were deployed at 2 meters below the surface and 2 meters above the seabed. The deployment was for 16 days between the 8th to 24th February 2005. Parameters recorded were the current speed (m/s), direction (degrees magN) and the pressure (dB).

**Figure 2.9. Valeport BFM 308 Direct Recording current meter.**

### 2.8.3 Water quality.

A series of surveys were carried out in the study area during spring and summer 2007 and winter 2008. Salinity and temperature profiles were taken at 1 m depth intervals at 7 stations in order to characterize and compare differences in the study area. Temperature readings were taken using a WTW portable oxygen meter. Salinity was measured using an Oxi 197, LF 196 conductivity meter and probe (Fig 2.10).

**Figure 2.10. The dissolved oxygen DO YSI Instruments, Y550A, Y58 and GPS (left) and the Oxi 197, LF 196 used for measuring salinity (right)**

**Figure 2.11. Van Veen grab (0.025 m$^2$)**

### 2.8.4 Granulometry.

Seabed sediment sampling for granulometric analysis was carried out in August 2007 using a hand operated Van Veen grab (0.025 $m^2$) (Fig 2.11) at 30 locations throughout the bay system. A sub-sample of sediment was taken from each grab and stored frozen at -20±1$^{o}$C until laboratory analysis by dry sieving (Folk 1974).

### 2.8.5 Sediment nutrients.

Sediment samples for measurement of nitrogen content were collected by grab at eight fish production sites, operated by Marine Harvest Ireland Ltd., between 2002 and 2006. Each year triplicate samples were taken from beneath the centre of each cage block and at the downstream end of each cage block. Each year triplicate samples were taken from beneath the centre of each cage block and at the downstream end of each cage block. Samples were transported as frozen and, after thawing, were oven dried overnight at 90$^{o}$C. Carbon and nitrogen content were analysed as percentage by dry weight sediment using a Perkin Elmer 2400 Series ii CHNS/O analyser.

### 2.8.6 Protected areas.

The Environment Heritage and Local Government is responsible, through the National Park and Wildlife Service, for the designation of conservation sites in Ireland. There three main types of protected areas designation in Mulroy Bay: Special Areas of Conservation SAC, Special Protection Areas, (SPA), the Natural Heritage Areas (NHA).The GIS data was downloaded from the web page url: http://www.npws.ie/en/MapsData/.

### 2.8.7 Data base components.

All data collected for classification of environmental parameters were layers consisting of 50 x 50 $m^2$ grid cells. All grid layers were incorporated into the GIS framework (Arc view 3.2 ESRI). The components of the spatial database used in this study are summarized in Table 2.1.

**Table 2.1. Principal database components used in this study.**

| Database Layer | Description | Supplier/Creator | Source resolution & projection |
|---|---|---|---|
| Nautical chart | Bathymetry map | UK Admiralty Chart 2699 | Lat/long |
| Bathymetry | Vector | Digitized | Lat /long |
| Bathymetry/ depth | Raster | Interpolated | Lat/long<br>50 x 50 m |
| Aquaculture sites licence | Vector and Points | Digitized and GPS | Lat/long |
| Coast line | Vector | Digitized | Lat /long |
| Protected areas | Vector | National Park and Wildlife Service Ireland | Irish grid reference system convert to lat/long |
| Mean current velocity | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Quiescent period | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Stratification index | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Seabed type | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Waste dispersion distance | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Oxygen depletion index | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Current speed max | Raster | Modeled/Author | Lat/long<br>50 x 50 m |
| Slope | Raster | Author | Lat/long<br>50 x 50 m |

## 2.9 GIS systems and Modelling Software.

The core hardware used for modelling was a Dell Precison Workstation, model 490, with twin 3GHz dual core processors, 4Gb RAM and running the Windows XP operating system.

The chosen GIS system was Arc View 3.2 ESRI which is primarily a basic GIS software suite for the integration and visualization of different sources of geodata sets. It was ideally suited for the objectives of this study for visual representation of model outcomes.

The hydrodynamic models were created using MOHID 3D developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Tecnico (IST), Technical University of Lisbon. MOHID has shown its ability to simulate complex features of the flows. It has been used, for example, in coastal circulation, nutrient loads and residence time models in several places around the world, recently, modelling the influence of nutrient loads in an estuary (Saraiva et al., 2007), modeling the temperate coastal lagoon (Vaz et al., 2007), oil spills forecast (Carracedo, et al., 2006) Modelling macroalgae (Trancoso, 2005), estuarine Plumes, (Vaz et al., 2009), effect of large scale atmospheric pressure changes on water level, (Canas et al., 2009) and the effect of the Bathymetric Changes on the Hydrodynamic and Residence Time in a lagoon (Malhadas, 2009), for more examples see http://www.mohid.com/Publications/JP.asp .

Vertical eddy viscosity/diffusivity was determined with a turbulence closure model selected from those available in the General Ocean Turbulence Model (GOTM) (Burchard et al., 1999) is integrated in MOHID 3D. In this application a 3D model forced with both tide and wind was implemented. At the boundary conditions the water level taken from the FES2004 global tide solution is imposed (Lyard et al., 2006).The neuro-fuzzy systems are applied in various domains e.g. control, data analysis decision support. The neuro-fuzzy software NEFCLASS- J for JAVA platforms (NEruro Fuzzy CLASSifier, see: http://fuzzy.cs.uni-magdeburg.de/nefclass/) (Nauck and Kruse 1999) was used. This program have been used in land soil erosion (Zhu et al., 2009), medical aplications, (Keles et al., 2007; Hardalac, 2008) and ground water vulnerability to nitrate (Dixon, 2005).

The software systems used throughout this study are summarized in Table 2.2.

**Table 2.2.Principal software and used in this study.**

| **Software** | **Description** | **Supplier/web** |
|---|---|---|
| ArcView 3.2 | GIS | ESRI |
| 3D MOHID | Hydrodynamic and water quality model | Open source.<br>http://www.mohid.com/ |
| FES2004 | Global tide model | Open source<br>http://www.legos.obs-mip.fr/en/share/soa/cgi/getarc/v0.0/index.pl.cgi?contexte=SOA&donnees=maree&produit=modele_fes |
| GOTM | General Ocean model Turbulence Vertical eddy viscosity/diffusivity turbulence | Open source.<br>http://www.gotm.net/ |
| NEFCLASS | Data analysis<br>Neuro fuzzy systems | Open source<br>http://fuzzy.cs.uni-magdeburg.de/nefclass/ |

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# Chapter 3 A three-dimensional hydrodynamic and particle tracking model in a shallow fjordic system: water circulation and exchange.

J. Moreno, T. Telfer, Campuzano, F.J and L.G. Ross.

This chapter describes the development of a 3D hydrodynamic model coupled to a particle-tracking model which is applied to water circulation patterns, dispersion processes and flushing and residence time in Mulroy Bay. A rigorous statistical testing of the sensitivity, calibration and validation of the model was also performed with the data available.This chapter forms the baseline for other parts of the thesis. The vertical discretization used provided five independent layers that have be extracted and incorporated into a GIS system.

The main author, J Moreno Navas, conducted all field work and developed all sub models and final models. Prof Lindsay G Ross and Dr Trevor C Telfer provided supervisory and editorial support throughout the whole study. Dr F J Campuzano provided expert assistance with 3DMOHID. The body of the text is presented as a publication-ready manuscript. This manuscript has been submitted to Environmental Modelling and Software, an international journal committed to the contributions on recent advances in environmental modelling and/or software, model development, model evaluation, process identification and applications in diverse sectors of the environment.

# A three-dimensional hydrodynamic and particle tracking model in a shallow fjordic system: water circulation and exchange.

**Authors: J. Moreno[1]* T. Telfer[1], Campuzano, F.J[2] and L.G. Ross[1].**

[1] Institute of Aquaculture. University of Stirling. UK

[2] Maretec, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

* Corresponding author: Institute of Aquaculture. University of Stirling. FK94LA. Stirling.UK (jmn1@stir.ac.uk) Tlf :01786767882 .Fax: 01786472133

**3.1 Abstract.** A 3D hydrodynamic model MOHID coupled to a particle-tracking model is applied to study the circulation patterns, dispersion processes and residence time in an Irish fjard, a shallow fjordic system that is host to many important aquaculture activities. The model was applied to two climatic situations; the first with no wind stress and the second with application of real time wind stress data from a nearby meteorological station. A Lagrangian method was used to study the transport and flushing processes. Instantaneous massive releases of 15000 particles from key boxes are modelled to analyse the ocean- fjord exchange characteristics. The relative absolute error, root mean square error and the index of agreement measure of the tidal elevation and the longitudinal and lateral velocities were determined between measured and predicted time series results to quantify the model performance.

The general flow circulation was characterized by several residual tidal eddies, with a clearly wind driven scenario. This study demonstrated the strong influences of wind forcing on circulation patterns and flushing characteristics of this restricted region. This model can be successfully calibrated and used in future studies of important issues concerning hydrodynamic activity, water quality and aquaculture activities.

**Keywords:** 3D hydrodynamic models, particle-tracking model, regions of restricted exchange.

## 3.2 Introduction.

Fjards are coastal inlets of glacial origin and similar to fjords in nature but they exist in low lying areas and thus are without high-sided borders. Fjards may be deep and long with sills or shallow with significant areas of sand and mud flats. These inlets are common in Scotland, Ireland and Finland. The variations depend on the geometry and hydrology of the adjacent watershed, the oceanographic conditions outside the fjard and fjordic systems and meteorological conditions (Pedersen, 1978). Fjards, like fjords, are considered as regions of restricted exchange (RREs), which in biological terms are defined as almost closed ecosystems showing less variability than the open coast or ocean. Their biological production and productivity is generally high (Brattegard, 1980). The surrounding lands are preferred sites for housing, while the waters are used for fisheries, aquaculture, navigation and recreation. All these activities increase the nutrient and pathogen loading and may increase the risk of eutrophication (Tett et al., 2003) and environmental problems, which may be intensified by poor water exchange.

Cross (1993) suggested that finfish net cage sitting should consider the circulation dynamics evaluating back eddy potential and mass transport potential for the site the dispersion. Therefore, numerical circulation models could provide a practical solution to the problem of coastal mixing and dispersion of wastes in areas with finfish aquaculture (Wildish et al., 2004).

Numerous studies have verified the importance of local wind on the upper layer circulation in enclosed water bodies such as fjords (Leth, 1995), estuaries (Geyer, 1997) and tidal lagoons (Dronkers and Zimmerman, 1982). If the width of the enclosed water body is small, sufficient to be able to neglect the effect of the earth's rotation in the governing equations, then there will be no Ekman transport and wind stress will only be in the direction of the wind. The significance of the Earth's rotation on the upper layer dynamics is given by the Rossby radius for the first baroclinic mode (equation 1)

$$a_1 = \left(g' h\right)^{1/2} / f \quad \ldots\ldots\ldots\ldots\ldots.. (1)$$

where, $g'$ is the reduce gravity, $h$ is the upper layer thickness and $f$ is the Coriolis parameter.

RREs with short flushing times will export nutrients and pollutants from upstream sources more rapidly than others and the flushing characteristics associated with water quality implications are important when conducting environmental impact assessments. Renewal time scales also characterize the retention of nutrient and the exchange between the water column and the sediment. The deposition of particulate matter and adsorbed species depends on the particle's settling velocity, water depth and particle residence time; a very important consideration for the fine fractions with lower sinking velocities (Braunschweig et al., 2003). Transport time has a number of defined measures (Monsen et al., 2002), the two most commonly used being "flushing time" and "residence time", where the flushing time is the ratio of the mass of constituent (water) in the water body to its rate of renewal and residence time is the time until the water volume at a specific location leaves the water body. Residence time in the systems are complementary each other and depend on the water volume in the location whereas flushing time is an integrative time scale for the entire embayment.

Simple tidal prism models have been used for a considerable period of time in tidal flushing calculations (Dyer, 1973; Takeoma, 1984). However Luketina (1998) indicated that generally the classical tidal prism method has never been properly explained and may not be formulated correctly. Various authors therefore have proposed a reformulated method. For example, Tkalich (1996) used a two box tidal prism method suitable for calculation of the bay-ocean water exchange.

Other issues with such models include the effects of seabed on water flow. Aldridge and Davis (1993) concluded that the volume of water flowing through a given section dropped when the friction coefficient was increased. In addition, they confirmed that the effect of spatial variation of the bed friction as a function of bed composition was shown to have a small effect on tidal currents but a significant effect on the bed stress derived from a three dimensional hydrodynamic tidal model of the eastern Irish Sea. They also found a limitation of limited area models where the solution can be dominated by the open boundary.

This paper describes the use of the hydrodynamic model MOHID 3D, to simulated key features of the tidal, wind induced circulation and the flushing time within Mulroy Bay Co Donegal, a fjardic system in an area of restricted exchange. The model describes spatial and temporal aspects of circulation and renewal time and helps to determine the influence of winds on circulation patterns. A modelling scenario was used which defined water movement from areas within the vicinity of fish farms situated in the bay.

## 3.3 Study area.

Mulroy Bay is as a fjardic inlet (shallow fjordic system) situated on the northern coast of Co Donegal, Ireland (55 15'N, 7 45'W). It is bounded on the west by the Rosguill Peninsula and on the east by Fanad Peninsula. It is a convoluted and complex environment, extending inland for about 19 km, with a range of hydrodynamic conditions (Fig 3.1). The whole area is a proposed Special Area of Conservation (SAC). Aquaculture is intensively developed within the fjard, with up 16 operators currently licensed for mussel, oyster, clams, scallops, abalone and salmon production.

The bay is divided into four main geographical areas: the Outer Bay, Northwater, Broadwater and the Narrows. The Narrows is further sub-divided into three sections each approximately 150-200 m wide, known as First, Second and Third Narrows

The bathymetry (Fig 3.1) was taken from UK Admiralty Chart Number 2698, but the area is not well charted and considerable changes of depths have occurred on the Bar (Outer Bay).

Broadwater and Northwater are not influenced by ocean swells, are sheltered from the wind by the low lying surrounding hills. With a maximum fetch of 11 km, it is rare to have significant wave action. The nearest meteorological weather station is located in Malin Head, 35 km to north east of Mulroy Bay.

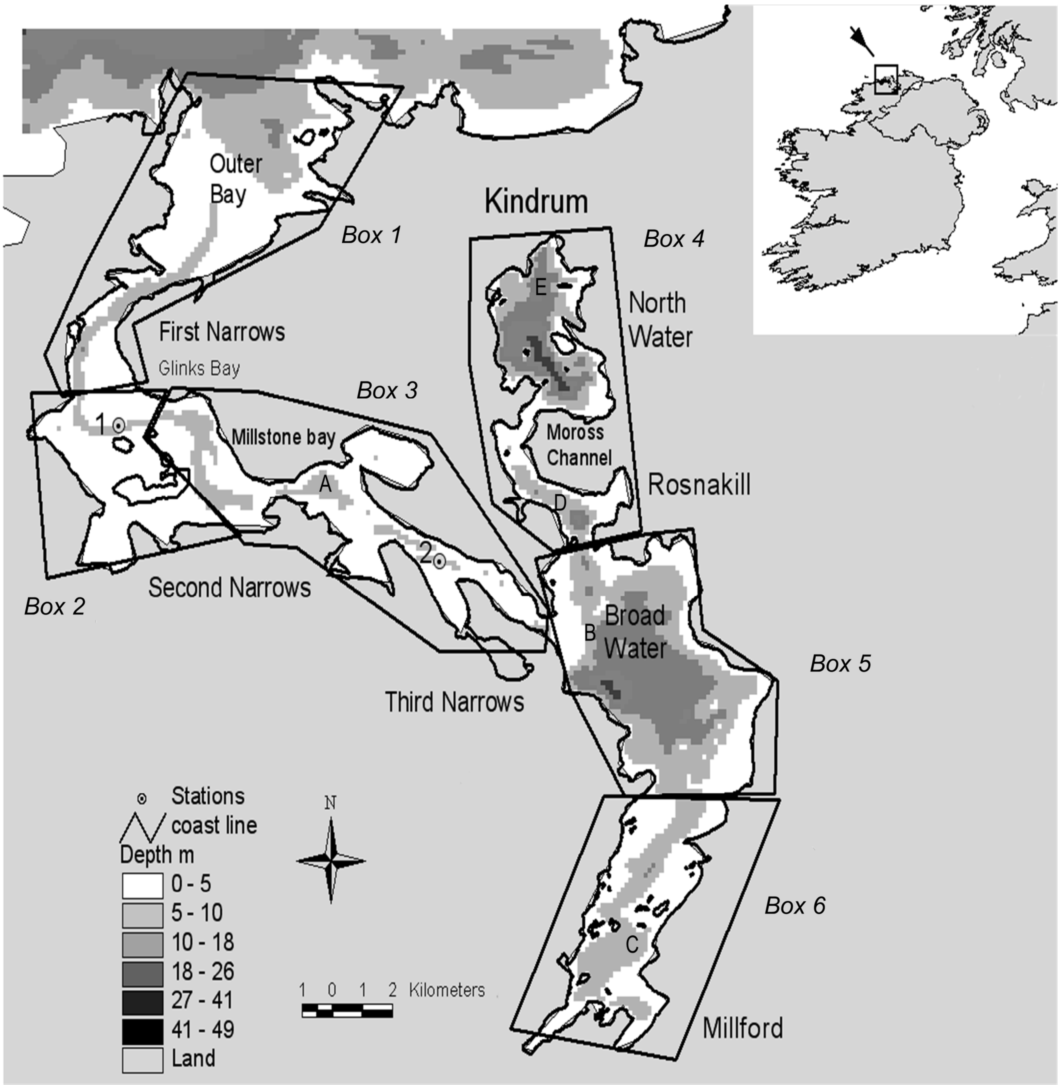

**Figure 3.1. The location of Mulroy Bay, Co Donegal, the sampling stations (A to E), the division of the fjard into 6 boxes, the bathymetry of the study area and the position of the two hydrological stations.**

The wind in 2005 had a mean velocity of 6.8 m/s and was predominantly from a south-westerly direction; 225° gridN (Met Eireann Institute). The average monthly air temperature recorded at Malin Head was 10.4° C with the highest monthly average temperatures in August. The average annual rainfall of 1245 mm was recorded at in Carrowkeel on the shores of Mulroy Bay. The tidal range in Mulroy Bay varies from 3.2 to 4.2m at the Bar in the Outer Bay to 1.2 to 1.6 m in Broadwater. The tidal stream is very strong particularly at the Narrows, Parkes (1958) quoted a delay of 143 minutes between the time of high water at the Bar, in the Outer Bay, and in Broadwater. Current speed measurements in the Narrows, taken over a 24 h period, show that the average flood tide velocity is larger than the average ebb tide velocity. The dominant flood current is about of 20 cm/s higher than the ebb current magnitude. Tidal current asymmetry may be caused by tidal harmonics constituents in forcing tide, generated by friction, tidal interaction with channel geometry and generated by basin hypsometry (Walton, 2002).

Temperature fluctuation within Mulroy Bay follows typical seasonal patterns for a temperate climate. Mean seasonal temperatures range from 6.2º C in January to 18ºC in August in Northwater and from 5.4º C in January to 17.9ºC in August in Broadwater (C-Mar. 2000).

The Irish Marine Institute maintains a network of temperature probes in the area, and the data at different depths can now be accessed via internet for the years 2004 to 2007.

url: http://www.marine.ie/home/publicationsdata/data/temperaturedata

The seasonal superficial temperature in 2005 resulted in a mean range from 6.7 ºC in February to 16.8ºC in July in Broadwater (Cranford Bay). The annual average was 11.3 ºC. The institute also maintains a Weather Buoy Network, and the buoy M4 recorded water temperature values in the Irish Sea in 2005 ranging from 7.4 ºC in February to 17.3ºC in July. Thermal stratification was observed in Northwater and Broadwater (C-Mar, 2000; Minchin, 1981) and in the southern reaches of the bay near Milford (Telfer and Robinson, 2003). No thermal variance with depth has been reported in the Narrows where currents are strong and the water column is well mixed.

There are no large rivers draining into the bay which could significantly affect salinity.

A shallow halocline can develop in parts of Northwater and Broadwater where the freshwater runoff lies on the surface during calmer weather. Salinity in the Narrows varies seasonally from 29.5 PSU in January to 34.7 PSU in August in Northwater and from 28 PSU in January to 35 PSU in August in Broadwater (C-Mar, 2000). A salinity depth profile, obtained in January 1999, C-Mar (2000) indicated that there was stratification in the southern region of the Broadwater probably caused by rain and freshwater draining into the area from the shore line, but have not found sufficient salinity data set to validate the model.

Flushing times calculated using the simple tidal prism method (C-Mar, 2000; Telfer and Robinson , 2003) have given varied results. The flushing time between Broadwater and Northwater to the ocean were 6.91 and 8.75 tides respectively according to (Telfer and Robinson, 2003) and 11.5 and 15 tides (C-Mar, 2000).

## 3.4 Numerical hydrodynamic model.

The hydrodynamic model MOHID 3D used in this work (Martins et al., 2001; Martins et al., 1998; Santos, 1995) solves the equations of three-dimensional flow for incompressible fluids and an equation of state relating density to salinity and temperature. Hydrostatic equilibrium and the Boussinesq approximation are assumed. The Coriolis parameter has been considered constant as the study area is small.

Following Martins et al. (2001), in the Cartesian coordinate frame the equations are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (2)$$

$$\begin{aligned} \frac{\partial u_1}{\partial t} + \frac{\partial (u_j u_1)}{\partial x_j} &= -fu_2 - g\frac{\rho_\eta}{\rho_0}\frac{\partial \eta}{\partial x_1} - \frac{1}{\rho_0}\frac{\partial p_S}{\partial x_1} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_1} dx_3 \\ &+ \frac{\partial}{\partial x_j}\left( \mathrm{A}_j \frac{\partial u_1}{\partial x_j} \right) \end{aligned} \qquad (3)$$

$$\frac{\partial u_2}{\partial t} + \frac{\partial (u_j u_2)}{\partial x_j} = fu_1 - g\frac{\rho_\eta}{\rho_0}\frac{\partial \eta}{\partial x_2} - \frac{1}{\rho_0}\frac{\partial p_S}{\partial x_2} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_2} dx_3 \qquad (4)$$
$$+ \frac{\partial}{\partial x_j}\left( \mathrm{A}_j \frac{\partial u_2}{\partial x_j} \right)$$

$$\frac{\partial p}{\partial x_3} = -\rho g \qquad (5)$$

Where $(u_i)_{ij}$ are the velocity components in the Cartesian $x_i$, $\eta$ is the free surface elevation, $\mathrm{A}_i$ turbulent viscosity coefficients, $f$ is the Coriolis parameter, $p_s$ the atmospheric pressure, $g$ is the gravitational acceleration, $\rho$ is the density and $\rho'$ its anomaly.

A single value for water density over the whole domain was calculated by the equation of state (Leendertsse and Liu, 1978) using the assumption that values for salinity and temperature were constant. These values were incorporated into the model parameters (Table 1).

Accurate bathymetry representation is one of the most important and fundamental requirements in hydrographic modelling (Cheng et al., 1991). The bathymetry was digitized from the UK Admiralty Chart and a bathymetric model was developed by interpolation to a 50 m grid resolution (Fig 3.2).

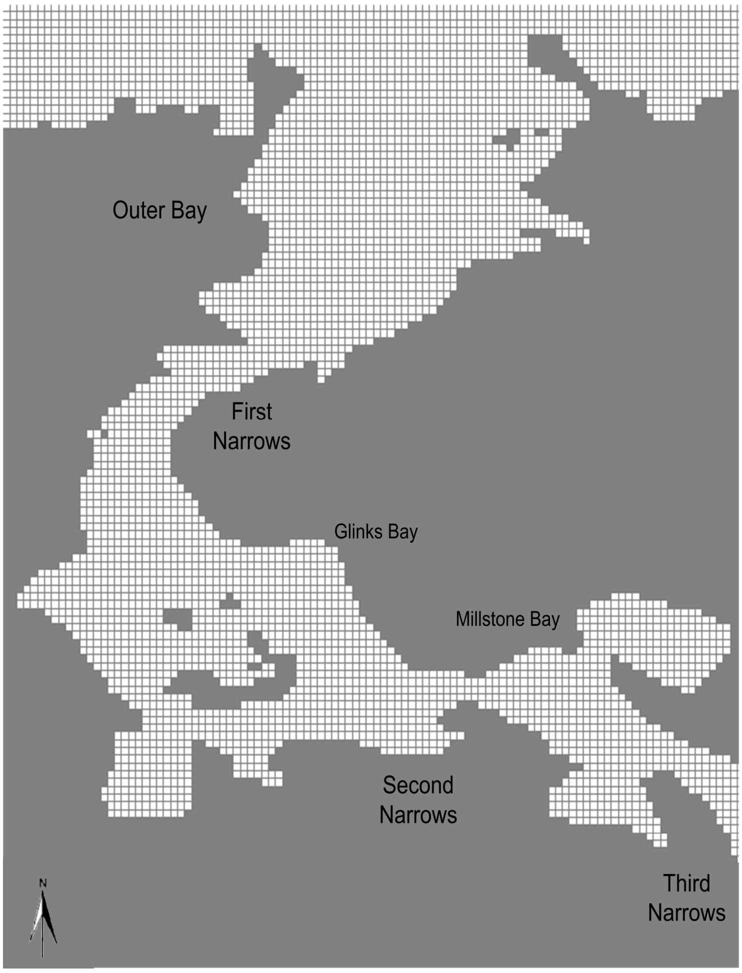

**Figure 3.2 Example of the high resolution finite element mesh used for the Mulroy Bay model, which used 193 x 244 cells in 5 vertical layers based on Sigma vertical coordinate.**

At model resolution the Courant-Friedrichs-Lewy stability condition (Equation 6) dictated a time step of $\approx$2s.

$$\Delta t < \Delta x / \sqrt{2gh} \quad (6)$$

where: $\Delta t$ is the time step, $\Delta x$ is the grid spacing, g is gravitational constant, h is the maximum depth in the calculation domain.

An Arakawa C grid was used for spatial discretization (Arakawa and Lamb, 1977).

MOHID allows several options for the vertical discretization: Cartesian coordinates, sigma coordinates or a generic vertical coordinate. In this study a sigma coordinate was chosen with 5 vertical layers (see Animation 1,2,3). This guaranteed that the layers were separate enough to prevent numerical instability in very shallow zones (Phillips, 1957). However, a sigma co-ordinate transformation has certain disadvantages. In transforming the curved physical region to the computational domain, the governing equations of flow and solute transport are also transformed, leading to more complex equations and some of the additional terms involving cross-derivatives. When large bathymetric irregularities exist, the layer thickness may be too large in deep water to represent 3-D features accurately (Lin and Falconer 2008). These authors suggest that if the area has a large tidal regime the use of fixed grids when flooding and drying may be extensive, for example in some UK estuaries.

The model used a semi-implicit ADI algorithm introduced by Peaceman and Racford in 1955 (Fletcher, 1991). This algorithm computed alternately one component of velocity implicitly while the other was calculated explicitly. This method has the advantage accruing from the stability of implicit methods without the drawbacks of computational expensiveness and associated phase errors.

Bottom stress is calculated following Backhaus (1985). It was parameterized using a quadratic law. $Cd$, the bottom drag coefficient, is calculated with the expression:

$$Cd = \left( \frac{K}{\ln\left( \frac{z + z_0^b}{z_0^b} \right)} \right)^2 \quad (7)$$

Where $K$ is Von Karman constant, $z$ is the observation length and $z_0^b$ is the bottom roughness length.

Vertical eddy viscosity/diffusivity was determined with a turbulence closure model selected from those available in the General Ocean Turbulence Model (GOTM)

(Burchard et al., 1999). The residual current $u_e$ is estimating by averaging the horizontal flow $u$ over a complete time period $T$:

$$u_e = 1/T \int_0^T u dt \qquad (8)$$

In this application a 3D model forced with tide and wind (Fig 3.3) was implemented at the boundary, and the water level taken from the FES2004 global tide solution is imposed (Lyard et al., 2006) .

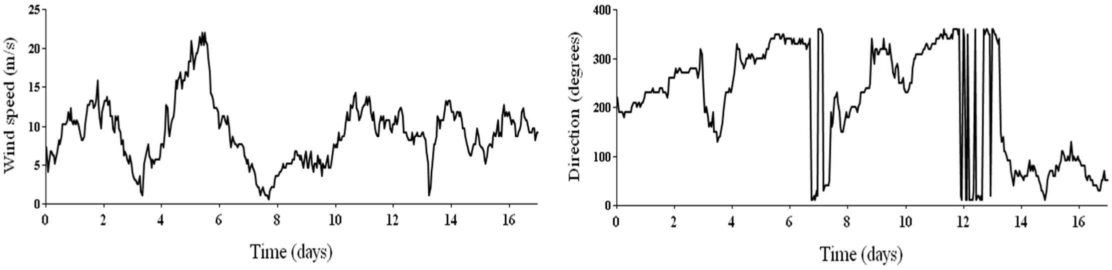

**Figure 3.3. Sample records of the direction and wind speed from Malind Head, used in the model. Data from February 2005.**

The FES (Finite Element Solution) model was based on the resolution of the barotropic tidal equation on a global finite element grid without any open boundary conditions and no assimilation, which leads to a solution independent of *in situ* data. FES2004 gave heights of tidal constituents (one of the harmonic elements in a mathematical expression for the tide-producing force with a ⅛° x ⅛° grid resolution for a global coverage, and provided the main tidal constituents M2, S2, N2, K2, 2N2, K1, O1, Q1). Wind was assumed equal in all domains to the one measured by the closest meteorological station. The parameters used for calculations are summarized in (Table 3.1). There are no large rivers draining into the bay which could significantly affect salinity and there was complete thermal vertical mixing of temperature in the water column with a mean of

6.67 ° C and 6.81° C at one meter and 10 meters depth respectably in February 2005 (source: Irish Marine Institute network of temperature probes in the area). The constant value of 32 psu at all depth in a one day salinity profile covering the whole area in Feb 2008 were measured (Institute of Aquaculture, unpublished data). It was incorporated in the model parameters (see table 3.1).

**Table 3.1. Parameters used in the calculations.**

| Physical parameter | Numerical value | Units |
|---|---|---|
| Time step: | 2 | s |
| Grid mesh: | 50 | m |
| Horizontal cells (x,y): | 192, 244 | |
| Vertical coordinate: | Sigma | |
| Vertical layers: | 5 | |
| Horizontal Eddy Viscosity: | 0.407738 | $m^2s^{-1}$ |
| Vertical Eddy viscosity: | 0.001 | $m^2s^{-1}$ |
| Drag coefficient: | 0.03 | |
| Wind rugosity coefficient: | 0.0025 | |
| River discharge: | No | |
| Temperature: | 7 | ° C |
| Salinity: | 32.6 | (psu) |
| Density: | 1025.434 | $kgm^{-3}$ |

A particle tracking model was coupled to the hydrodynamic model to describe the movement of passive tracers. This model assumes that the velocity of each particle ($u_p$) can be split into a large scale organized flow characterized by a mean velocity ($u_M$) provided by the model and the smaller scale random movement ($u_F$) given by:

$$u_P = u_M + u_F \quad (9)$$

The particle tracking model used computed the equation:

$$\frac{\partial x_i}{\partial t} = u_i(x_i, t) \qquad (10)$$

Where $u_i$ is the mean velocity and $x_i$ the particle position. This equation was solved using the explicit method in equation 10.

$$x_i^{t+\Delta t} = x_i^t + \Delta t u_i^t \qquad (11)$$

The random movement was calculated following the procedure of (Allen, 1982). The random displacement was calculated using the mixing length and the turbulent velocity standard deviation provided by the hydrodynamic model.

## 3.5 Materials and methods.

Hydrographic measurements were taken from two stations within Mulroy Bay (Fig 3.1) using two Valeport BFM 308 Direct Recording current meters deployed at 2 meters below the surface and 2 meters above the seabed. The deployment was for 16 days between the 8th to 24th February 2005. Two cross-sections of the data were separated for use in the calibration and validation processes, independently (cross validation).

Parameters recorded were the current speed (m/s), direction (degrees magN) and the pressure (dB). It must be noted that during deployment there were evidently several periods where the sea bed current meter at Station 2 was not recording flow. It was likely that in these periods the impeller was temporary fouled, but the data was still regarded as adequate for the needs of this study.

The wind data for the modelled period (Fig.3.3) were acquired from the Irish Meteorological Office. Met Eireann ( www.met.ie).

In order to characterize the study area and provide environmental information for inclusion into the model, salinity (Oxi 197, LF 196 conductivity meter and probe) and temperature (WTW portable meter) profiles were taken in February 2008 at 1 m depth intervals at stations A, B, C, D and E (see Fig 3.1). In addition, temperature data from the Irish Marine Institute (network of temperature probes) were obtained for February 2005.

Sensitivity analysis studies the relationships between information flowing in and out of the model. The analysis can be employed prior to a calibration exercise to investigate the tuning importance of each parameter and to identify a candidate set of important factors for calibration (Saltelli, 2000). Sensitivity tests were initially carried out in order to analyse the sensitivity of the hydrodynamic model to variation.

The sensitivity of the model was tested to variation in horizontal eddy viscosity and drag coefficient following Walstra et al. (2001), wind rugosity coefficient and wind directions. These parameters were varied and the results (Fig 3.4) were compared to those from the reference run with a drag coefficient of 0.005, horizontal eddy viscosity of 0.407 $m^2 s^{-1}$, wind rugosity coefficient of 0.005 and wind direction of 0º N degrees and wind speed of 7 m/s ('Ref'in Fig 3.4).

Several sensitivity runs were carried out over a period of one day (9/2/05) to gain an overview. The parameters were varied one at time by an incremental proportion of their values and this was repeated using two parameters at a time to test for interaction between them. The RMSE as in equation 15, was calculated to compare the time series of current speed from the different runs (fig 3.4,a,b), and the time series errors in the current speed, current direction and tidal elevation in a series of runs with constant wind directions and speed (fig 3.4, c). The percentage deviation from the reference parameter set was calculated to assess the sensitivity to the mean current velocity, mean current direction and mean tidal elevation (fig 3.4,d). It is important to note that the measurement data set is not used in this analysis.

During the model calibration a period of two days was selected (8-9/2/05). High values of drag coefficient were expected, and so this parameter was modified and the model was run for several values between 0.0045 and 0.05. In the calibration process the RMSE was computed between predicted and observer flow values. The value of Cd that minimized the error, Cd = 0.03 was adopted for use. For the validation process the relative mean absolute error (RMAE), the root mean square error (RMSE) and the index of agreement (IoAd) were computed as in equation 14,15 and 16 respectively.

The RMAE has been used by several authors to the evaluate numerical model results, (Fernandes et al., 2001; Sousa and Dias, 2007; Sutherland et al., 2004) and is given by:

$$RMAE = \frac{\langle |Q_m - Q_c| \rangle}{\langle |Q_m| \rangle} \quad (14)$$

where $Q_m$ and $Q_c$ are the measured and computed velocity vectors respectively.

The preliminary classification of RMAE ranges suggested by (Walstra et al., 2001) is shown in table 3.2.

**Table 3.2. Classifications error for RMAE (after Walstra et al., 2001).**

| Classification | RMAE |
|---|---|
| Excellent | < 0.2 |
| Good | 0.2-0.4 |
| Reasonable | 0.4-0.7 |
| Poor | 0.7-1 |
| Bad | >1 |

The root mean square error (RMSE), records in real units the level of overall agreement between the measured and the computed datasets.

$$RMSE = \sqrt{\frac{\sum_{i=}^{n} (Q_m - Q_c)^2}{n}} \quad (15)$$

where $Q_m$ and $Q_c$ is the measured and computed velocity vector respectively.

The index of agreement measure (IoAd) (Watson et al., 2007; Wilmott, 1981)) is given by:

$$IoAd = 1 - \frac{\sum_{i=1}^{n} (Q_m - Q_c)^2}{\sum_{i=1}^{n} \left( \left| Q_c - \overline{Q_i} \right| + \left| Q_m - \overline{Q_i} \right| \right)^2} \quad (16)$$

where $Q_m$ and $Q_c$ are the measured and computed velocity vectors respectively and $\overline{Q_i}$ is a time mean velocity vector measured.

This descriptive statistic reflects the degree to which the observed variation is accurately estimated by the simulated variation. The maximum positive score of 1 represents a perfect model. The IoAd has been used to evaluate numerical model results by several authors (Fernandes et al., 2001; Warner, 2005). These parameters are summarized in Tables 3.3 and 3.4.

Following Braunschweig et al. (2003), the fjard was divided in 6 boxes which covered the whole area of the inlet (Fig 3.1). The boxes are used in two ways: for release of the Lagrangian tracers (2500 particles in every box, 15000 in total) and to examine the tracers which pass through them. A box’s average residence time was defined as the time needed until the water volume initially in a given region was replaced by new water. This were computed by releasing an amount of tracers with a volume equal to the entire water body. The water fraction inside the box $i$ in each instant of time, with origin from box $j(f_{i,j})$ was calculated as:

$$f_{i,j}(t) = \frac{V_{i,j}(t)}{V_{i,j}(0)} \quad (17)$$

where $V_{i,j}(t)$ is the volume of tracers emitted in box $j$, present inside box $i$ at time $t$ and $V_{i,j}(0)$ represents the water volume in box $i$ at the beginning of the simulation. For the special case $i = j$ the average residence time for a given box is computed. When $V_{i,j}(t)$ reaches zero all the water is renewed in the box and the box's average residence time is found.

The e-folding time approach was used to define the flushing time, which is the time required to decrease the initial number of particles in a particular region by a factor of $e$, the flush out a fraction $1 - e^{-1} = (1 - 0.36788)$ of particles deployed inside the fjard. This approach has been used by several authors (Abdelrhman, 2005; Bilgili et al., 2005; Inoue and Wiseman.W.J.Jr, 2000). The particle tracking model was used with depth one layer only, behaving as a 2D depth integrating model. Most parts of the fjard are shallow and the effect between layers was not considerable and is only present in the superficial part. This justified the use of the two dimensional approximation as the computational effort for 3D would be excessive. The number and the location of the boxes were arranged to fill the whole area in order to provide a value for global residence time. The influences of the wind over the renewal process were also studied. Two scenarios were used, one with wind and the other without.

## 3.6 Model results.

The time periods modelled were forced the model using the real data set, in which the average wind velocity of 9 m/s and the average wind direction is 222º, which is a good approximation of the real annual wind characteristics from the MET and which provided acceptable wind forcing in the model. The meteorological data sets used are shown in the Figure 3.3.

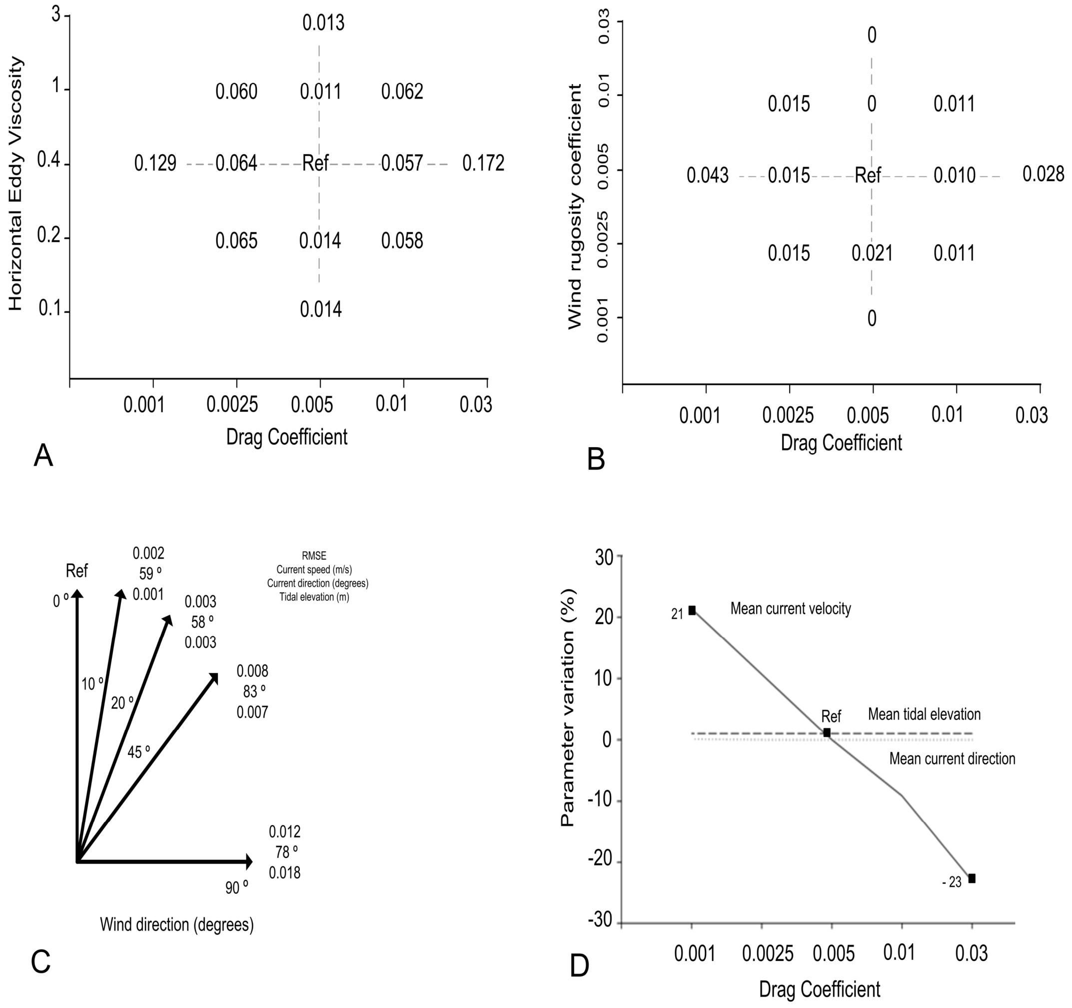

**Figure 3.4. Sensitivity analysis; (A) effect of drag coefficient and horizontal eddy viscosity and (B) drag coefficient and the wind rugosity coefficient on the RMSE of current speed time series' (12 model runs). (C) effect on current speed, current direction and tidal elevation time series on the RMSE, with different constant wind direction and speed. (D) percentage of variation of mean current speed, mean tidal elevation and mean current direction.**

The sensitivity analysis (Fig.3.4A) showed that the variation from the reference run ("Ref") did not have a large influence on the modelling predictions, with the drag coefficient having the highest relative sensitivity. Increasing or decreasing this coefficient from the reference run caused linear variation in the mean current velocity (not shown) and the RMSE. Fig. 3.4D shows that mean current speed changes significantly as expected (+21 to -23 %), if the drag coefficient is modified, although no significant variation was found in current direction and tidal elevation (both close to zero). No significant variation was found by modifying the horizontal eddy viscosity and wind rugosity coefficient (Fig 3.4B). A significant variation was found in current direction in the constant wind scenarios.

There are no large rivers which could significantly affect salinity draining into the Mulroy Bay. Results for water temperature in Broadwater show that there was complete thermal vertical mixing of temperature in the water column in February 2005 with a mean of 6.67 ° C and 6.81° C at 1 m and 10 m depth, respectively. (source: Irish Marine Institute network of temperature probes). In February 2008, temperature profiles ranged between 6.1 °C to 6.6 °C and showed complete thermal vertical mixing in the water column over the whole study area. Results for February 2008 showed no large changes in salinity with depth (Fig 3.5) thus no stratification. Mean water column salinity values ranged between 30.8psu and 32.6 psu, with the lowest value being found at Kindrum and in the Moross Channel which may due to rain or freshwater draining.

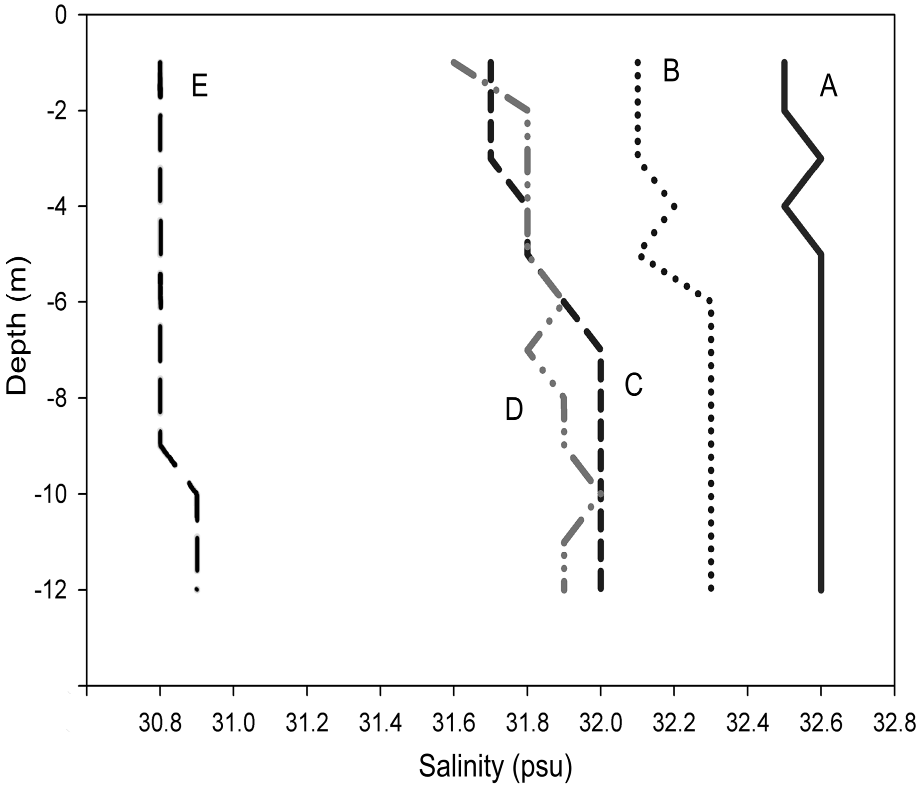

**Figure 3.5 Examples of salinity vs. Bottom-depth plot from the stations illustrated the difference in salinity between zones in winter season.**

For sea surface elevation, the calculated values of IoAd were close to 1 and low values of RMAE reveal a good agreement between the prediction of the model and the observation (Fig 3.6). The RMSE value of 0.275 m suggests that the model did not produce highly accurate tidal elevation values (Table 3.3) due to the bathymetry and the use of the FES2004 model for forcing the 3D model in the open boundaries.

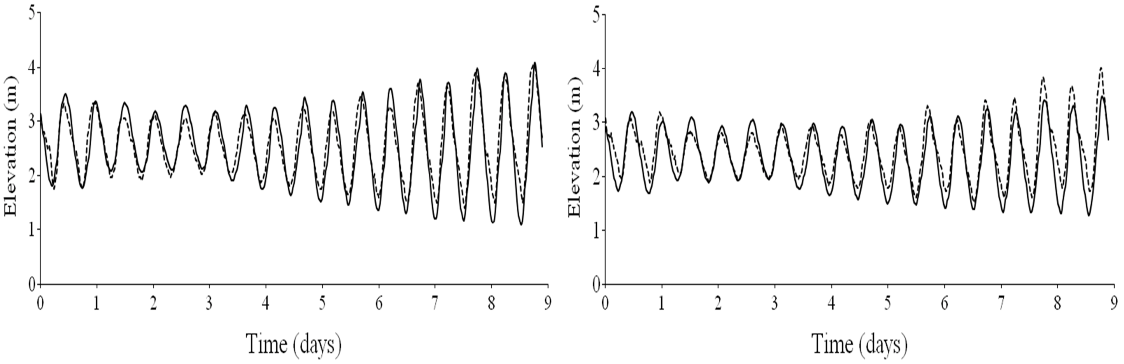

**Figure 3.6. Water level time series at the two station in Mulroy Bay shows in fig 1 comparing observed (dotted line) with modeled (solid line) data. Station one (left) RMAE = 0.025, IoAD= 0.95. Station two (right ) RMAE = 0.057 , IoAD= 0.92**

The values of the observed and modelled mean current velocity at the two stations, were similar with little differences (Table 3.3). For general comparison the RMSE values for the two stations were between 0.1159 m/s and 0.1359 m/s. The highest RMSE value was at station 2 in the bottom layer (Table 3.3), because there were several periods where the sea bed current meter at Millstone did not record flow. The current direction means were almost identical at both stations, showing that the model can predict the current direction accurately (Table 3.3).

The IoAd values were high even with the gaps in data, the minimum value being 0.762 at Station 2 for the seabed measurement. The high values demonstrated a good approximation between modelled and measured current intensity data sets (Table 3.3).

At station 1 the model agreed very well with the eastward velocity measurements (Fig 3.7) surface and the bottom layers, with IoAd values close to 1 and low values of RMAE (Table 3.4) which were within the excellent category according to Walstra et al, (2001) (Table 3.2).

**Table 3. 3.Values of the mean intensity measured (Mean Int me) and modelled (Mean Int mo), RMSEi, IoADi in for the intensity values, current direction measured (Dir me) and modelled (Dir mo), IoADe RMSEe, RMAEe for the elevation values for the two stations (st1, st2) at the surface (sup) and at the bottom (bed).**

| St1 | Mean int me | Mean int mo | RMSEi | IoAdi | Dir me | Dir mo | IoAde | RMSEe | RMAEe |
|---|---|---|---|---|---|---|---|---|---|
| Sup | 0.379 m/s | 0.394 m/s | 0.122 m/s | 0.903 | 180 | 183 | 0.950 | 0.275m | 0.025 |
| Bed | 0.329 m/s | 0.364 m/s | 0.121 m/s | 0.896 | 180 | 181 | | | |
| St2 | Mean int me | Mean int mo | RMSE i | IoAD i | Dir me | Dir mo | IoAde | RMSEe | RMAEe |
| Sup | 0.383 m/s | 0.467 m/s | 0.115m/s | 0.903 | 227 | 222 | 0.927 | 0.2723m | 0.057 |
| Bed | 0.185 m/s | 0.273 m/s | 0.135m/s | 0.762 | 227 | 221 | | | |

**Table 3.4. RMAE, RMSE, and IoAD for the eastward (U) and northward (V) velocities at the superficial (s) and the bottom (b) for the stations.**

| Station 1 | RMAE | RMSE | IoAd |
|---|---|---|---|
| Us | 0.008 | 0.123 m/s | 0.971 |
| Vs | 0.54 | 0.008 m/s | 0.341 |
| Ub | 0.05 | 0.126 m/s | 0.976 |
| Vb | 0.28 | 0.057 m/s | 0.620 |
| Station 2 | RMAE | RMSE | IoAd |
| Us | 0.3 | 0.138 m/s | 0.960 |
| Vs | 0.05 | 0.08 m/s | 0.980 |
| Ub | 0.39 | 0.12 m/s | 0.929 |
| Vb | 0.18 | 0.07 m/s | 0.937 |

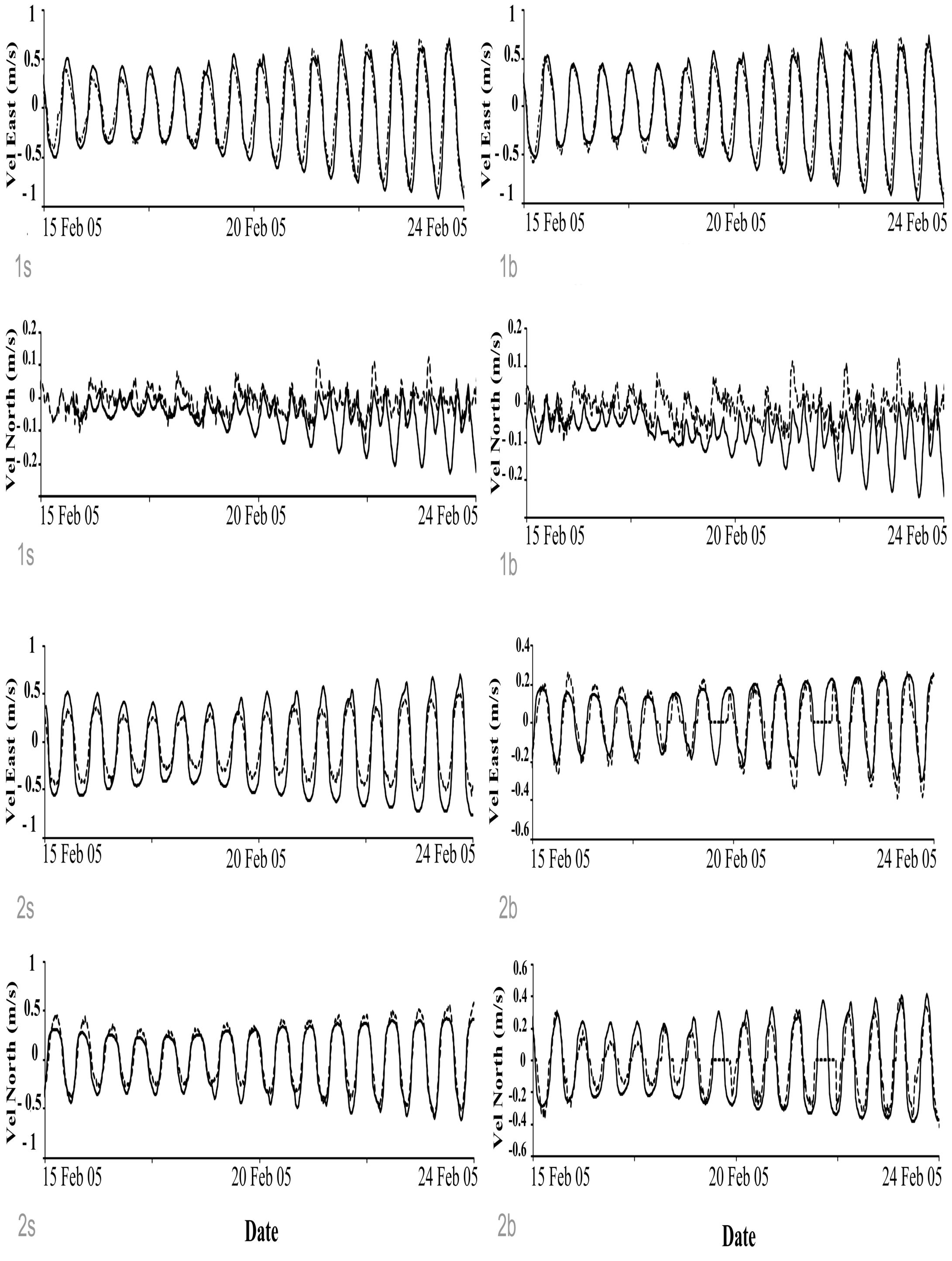

**Figure 3.7. Time series of the eastward and northward velocities in Mulroy Bay measured (dotted line) and modelled (grey line) at the two stations 1 and 2 at the surfaces (Fig.1S ,2S ) and at the bottom (Fig, 1B, 2B). Values of RMAE, RMSE and IoAd are given in table 3.6 .It must be noted that during deployment there were evidently several periods where the sea bed meter at station 2 recorded no flow.**

The northward velocity results were more complicated (Fig 3.7), with the mean modelled and observed values close to zero, so the influences on the final intensity and direction of the flow will be low. The highest RMAE value was 0.54 (Table 3.4). The model was not able to predict accurately this velocity component with very low values and the IoAd values were low, however as shown in (Table 3.4), although the model provided a very good approximation of current speed and direction, the northward velocity influences were low in the total intensity.

At station 2 the model agreed well with the northward and eastward velocities measured at the surface and the bottom (Fig 3.7), with IoAd values close to 1 and excellent and good values of RMAE (see Tables 3.3 and 3.4).

## 3.7 Circulation.

Knowledge of the residual velocity field (the displacement of water over a complete tidal cycle divided by the tidal period) helps the understanding of long term water exchange inside the fjard, and for that reason the residual flow for an entire tidal period was computed. The Narrows of Mulroy Bay are the region with strongest velocities (Fig 3.8, Animation 4), with the maximum velocity modelled in the proximity of the second narrow of about 2.5 (m/s) similar to that measured by Nunn (1996).

A very clear circulation structure can be identified with an anticlockwise residual tidal eddy in the Millstone area. In the Narrows the model showed the same current patterns in all wind scenarios and the three vertical layers, top, medium and bottom were similar due to the shallow depth (Fig 3.8).

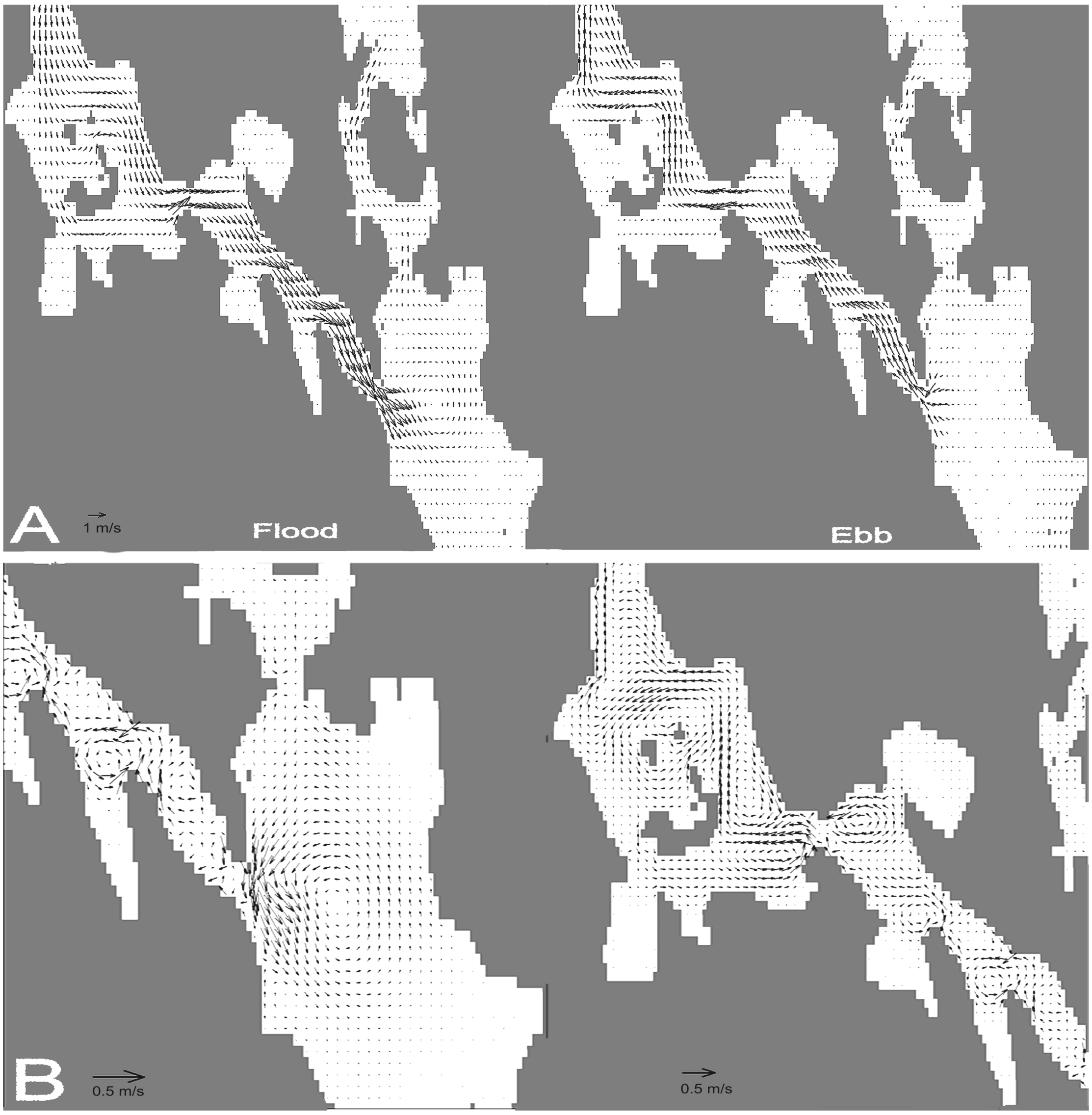

**Figure 3.8. Snapshots of the surface current, at ebb and flood A, and the residual circulation, B, in the middle layer of Broadwater and the channels during the period modelled. The model used real wind data and the arrows show the direction and the speed of the current.**

In the third and innermost part of the Narrows the proximity of the current stream, the very shallow depth and presence of rocks created a flood tide current jet into the Broadwater that influences the internal circulation structure (Fig 3.8). The northern part of Broadwater was dominated by a large anticlockwise residual tidal eddy close to the entrance to the Narrows, which was evident in the all vertical layers. A strong residual velocity flowing to the north was identified in the middle and bottom depth layers in Broadwater. In the mouth two Eddies were modelled at the medium depth (Fig 3.8).

The Kindrum area is connected with Broadwater by the Moross channel the residual velocity a main north flows cross the area at mid-water and bottom depth (Fig 3.9). At the mouth of Moross an eddy was clearly visible. In the surface layer the water flow travelled in a southerly direction and was probably dominated by the wind driven forces.

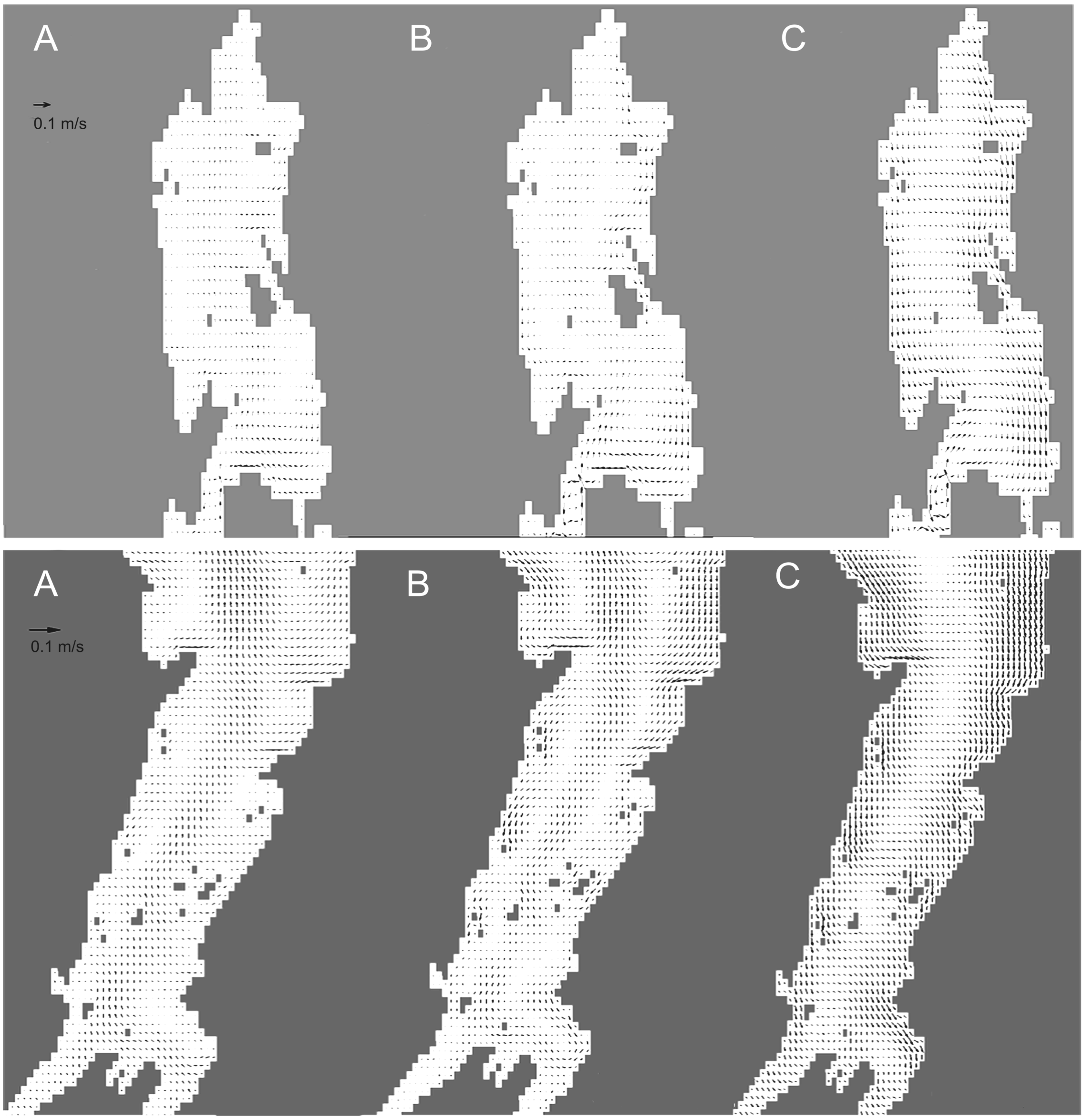

**Figure 3.9. The residual circulation in the Kindrum ,Broadwater and Millford areas in the three layers, (A bed, B middle and C surface depth) during the period modelled.**

When there was no wind forcing applied to the model the residual velocity was insignificant in the north part of Kindrum, which is sheltered by hills. This is probably the most realistic scenario for this sheltered area. A clockwise eddy was modelled in the area connected to the Moross channel in the mid-water layer. However, the figure clearly showed a wind driven scenario in the three layers system. When wind was taken into account a residual current in the direction of the wind stress was demostrated in the surface layer, a return current was found in the deep central part at the bottom and mixed residual current directions in the medium layer.

In Broadwater's central and southern section, water flows to the south in the superficial layers were identified very close to the shore line and flowed to the north in the centre of the water body (Fig 3.9). In the scenario of no wind (not shown in the figures), it is clear that the residual velocities were insignificant.

## 3.8 Flushing and Residence Time.

The water volume computed at neap is $2.6x10^8$ $m^3$ while in the spring period it is $3.4x10^8$ $m^3$. The e-folding time (the particle fraction value of 0.36) was about 10 days in the scenario of including real wind data and 17 days without wind (Fig 3.10, Animation 5). The residence time in the three boxes that cover the channels (Boxes 1, 2, 3) are consequently low, reaching the e-folding value of 0.36 in less than two days and with no evidence of wind influences. The Kindrum and Moross channel (Box 4) never achieved the e-folding value within the 20 days period modelled. The total percent of losses are 30% with no wind and 50% with wind. The two boxes, 5 and 6 in the Broadwater area, achieved the e-folding value at 11 and 8 days, respectively, with wind and at 12 days without wind, box 6 achieved e-folding value at 12 days but box 5 has approximately 50% loss and never achieved the e-folding value in the time modelled.

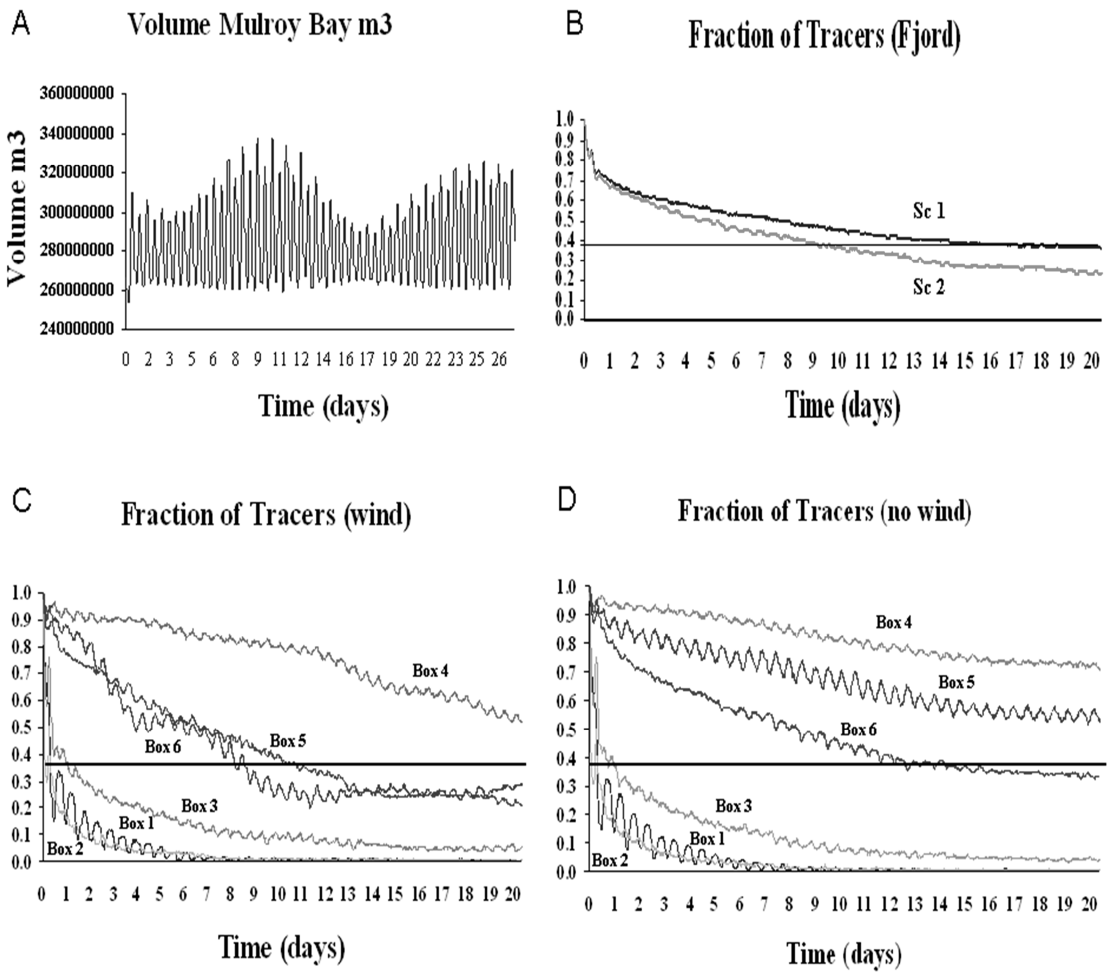

**Figure 3.10. A: Evolution of the water fraction in the whole fjord. B: fraction of tracers after 20 days for no wind ( B sc1), real wind ( B sc2), fractions of the tracers in every box in the two scenarios (C,wind and D no wind). The e-folding threshold is shown as a black horizontal line.**

## 3.9 Discussion.

The numerical modelling was challenging because of the lack of information on factors such as the sea bottom type for the drag coefficients, the model for forcing by tidal constituents provided by the FES2004 and the incomplete bathymetry and its change with time. It is also important to note that these water bodies were very narrow and therefore some differences may be explained by insufficiently detailed bathymetry.

The high resolution grid of 50 x 50 metres was appropriate and provided a good approximation of the actual topography within the Narrows area. Sousa and Dias (2007) used a 40x 40 meter resolution grid in similar narrow systems to good effect. A further sensitivity analysis using the model presented in this paper investigating different grid resolutions would be worthwhile

The vertical discretization used provided five independent layers that can be extracted and incorporated into a GIS system to allow input into a wide range of environmental modelling projects for coastal aquaculture activities. In such activities and applications using a 2D model, with a depth averaged approach, will not provide much needed differential information for near seabed environments. A 3D approach, as used in the present model, is thus more appropriate for modeling environmental factors in relation to coastal aquaculture.

Sensitivity analysis showed that variation in the eddy viscosity and wind rugosity coefficient does not have a large influence, while the drag coefficient has the highest influence. Around the reference parameter set, a linear effect of drag coefficient is assumed. Therefore, appropriate parameterisation is most important for this parameter. Similar conclusions were found by (Fernandes et al., 2001) and (Walstra et al., 2001). Little changes in the wind directions may caused significant variations in current directions and must be taken into account in scenarios where is considered constant wind direction and speed and it can be a source of errors due a extrapolating winds from single and multiple sites.

In six tidal channels with the same configuration at Mulroy Bay, (rocky, gravelly, rippled and indistinct), Sternberg (1968) firstly examined the friction coefficient used by several authors and concluded that this can vary from about 2.4 $x10^{-3}$ to 5.0 x $10^{-2}$. He found the value for the drag coefficient at 100 cm above the bed the magnitude varied from 3 x $10^{-4}$ to 3 x $10^{-2}$. Ludwick (1975) carried out a similar study at the entrances of Chesapeake Bay and found a mean value of 1.3 x $10^{-2}$ with two thirds of the values obtained between 3.5 x $10^{-3}$ to 5.4 x $10^{-2}$. Nowell et al. (1981) report an increment of the roughness caused by animal tracks.

Whitehouse and Chesher (1994), describe a review of field measurements concerning seabed roughness length throughout a tidal cycle. A detailed examination was carried out by Soulsby (1983), providing typical values of the roughness length and the drag coefficient for different bottom types. He noted that the value of the friction coefficient at 1 m above the seabed varied by a factor of 4 from the smoothest to the roughest substrate, illustrating the danger of using a constant drag coefficient for all substrates, this is the case in the present study but no previous information about bottom types available for inclusion in the parameterizations of the model. The friction coefficient of 0.03 used in this study is in the same order as those of the authors mentioned above

The interaction between submerged vegetation and hydrodynamics has also been investigated. Houwing et al. (2002) examined this interaction using the work of several authors and showed that there is a clear reduction in current velocity, current redirection or possibly a blocking effect of the current and a dissipation of wave energy. Seaweed and sea grass cover have been found in several areas and either may increase the bed drag coefficient value.

The hydrodynamic measurements used to validate the model were carried out in Mulroy Bay between 15 to 24 /02/05 (9 days in total). Such measurements give a good indication of the fjardic circulation. Several authors (Fernandes et al., 2001; Sousa and Dias 2007; Sutherland et al., 2004) have used one or two days of such data to calibrate and validate models successfully. It was not possible to perform a harmonic analysis in order to evaluate the model, as no reliable information was available and the tidal period recorded over 15 days, is not long enough for an accurate harmonic analysis.

In general the RMAE values were between 0.08 and 0.54, and the model gave a good representation of the 3D tidal flow characteristic in the area. A comparison between modelling predictions for the longitudinal and lateral velocities and field measurements indicate that the model reproduces well the behaviour of the system. However the northward velocity had the highest values of RMAE and RMSE showing that the model did not predict this velocity component accurately, but the model did provide very good approximation of current speed and current direction and the northward velocity influences were low (Table 3.5). The RMSE values for sea surface elevation were also be considered acceptable, ranging about 10-15 % of the local amplitude.

The magnitude of the residual circulation and spatial variation of the tidal velocity distribution are determined to a large extent by the fjord geomorphology. The residual circulation is generated by wind, interactions of the tidal flow with the bottom topography and shoreline geometry and in this case not by density differences. The area had no influence from fresh water inflow and the irregular topography and winds are the most important factors. As river inflow is very low no important density stratification will occur and the water body is well mixed vertically. The vertical and horizontal variations found in salinity and temperature in winter were insignificant with less than 2 psu difference between stations and almost the same value of temperature over the study area, for these reasons a constant value of density in the whole area was used assumed for the period modelled. We consider these to be a good approximation of these environmental factors and the particle tracking over the time modelled is likely to be unlikely to be affected by this approximation and assumption.

In areas where the tidal currents are weak, wind driven currents may develop more strongly and become the principal agent of mixing and renewal of the fjord waters. The wind stress on the water surface induces horizontal circulation and as the wind is predominantly from a south-westerly direction the fetch is almost the maximum longitudinal distance of the fjord. In Broadwater and Kindrum areas a wind driven scenario with a three layer residual current in the direction of the wind stress was computed in the superficial layer, with a return current in the deep central part at the bottom and mixed residual current directions in the medium layer. The narrows and channels were not affected by the winds, although they have a large tidal velocities and irregular bottom topography and consequently have strong vertical mixing.

The current eddies were the major circulation features that define the study area. Zimmenman (1981) studied the dynamic characteristics of residual tidal eddies and the fluid response of an irregular sea bed or coastline to the current tidal regime. He classified and described different situations according to the geomorphologhical background into three types: residual basin circulation given by the ebb- flood interaction generated by frictional boundary layers in a semi enclosed basin; headland eddies around a coastal promontory where the tidal flow was accelerated and decelerated in the current direction and had a maximum near the headland and finally sand ridge eddies when the tidal current crosses a submarine sand ridge and the flow is accelerated going up the slope and decelerated going down the slope. The first and second scenarios described the formation of the numerous eddies in Mulroy Bay well, based on the ebb and flood surpluses in an enclosed basin. The relatively shallow narrows and channels create a series of streams and flows against rocks forming ebb-flood tidal current jets that influenced the internal circulation structure and create several eddies.

Dronkers and Zimmerman (1982) found that a strong vertical mixing does not necessarily imply a strong longitudinal mixing or a high flushing rate and so the fluid particles which are introduced into the fjord will remain there for some time. From this, these authors suggest that specific ecosystems may develop, different from those in the sea.

Mulroy Bay is an enclosed body of water with areas of restricted exchange, resulting in potential confinement of larvae and self-recruitment. Heipel et al. (1999) noted the distinctive nature of populations of *Pecten maximus,* in Mulroy Bay where the lowest genetic variability was recorded from this enclosed habitat. The author also suggested that hydrographic features like tidal circulation systems, can potentially restrict distribution and lead to differences in size, age, and genetic structure between different fishing grounds.

A comprehensive study of the ecology of fjord ecosystems must include the evaluation of appropriate hydrodynamic time scales. Tartinville et al. (1997) suggest that numerical modelling is capable of estimating the residence time with a high spatial resolution, and this enables a range of sensitivity analyses to be carried out, which helps understand the hydrodynamics of the area and the role of flow forcing factors. As expected the wind had an important role in the flushing characteristics of the area. This is clearly seen in the differences modelled with and without wind. The flushing time approach to define the exchange in a particular region, and corresponds to 5400 particles to be exported to the sea in the case of the whole area initially filled with 15000 particles. Fig 3.10 shows that the e-folding periods for boxes were between one day and more than twenty days. As a whole the fjord system flushed roughly between 10 to 17 days in the different scenarios. The effect of the initial particle release time (spring or neap tidal period) on the predicted residence time values requires further investigations.

The results of this study suggest that the residence time in Mulroy Bay varies significantly in space. Three regions, can be differentiated, a) the Narrows with low values of e-folding due to shallow depth, high speed currents and no effect of the wind stress, b) Broadwater which is affected by the narrowness of the channel that connects different areas, increased e-folding time, and also by the wind stress and, c) the Kindrum-Moross channel as expected with highest level of e-folding and considerably affected by the wind. The Kindrum area is the most sheltered against the winds and using the residence time calculated in the scenario without wind, it is clear that the pelagic larvae of *P. maximus* could spend the entire pelagic phase in the same area (Le Pennec et al., 2003). These results differ from those of Telfer and Robinson (2003) and C-Mar (2000), who calculated the residence and flushing time from tidal prisms. The flushing time modelled is greater than the values provided by the tidal prism. Braunschweig et al. (2003) suggested that the definition of the Lagrangian approach make it difficult to define residence and flushing times and could lead to excessively high values as the water is never fully replaced. Taking into consideration the tidal prism methodology, a shorter flushing time maybe expected. The simple box models do not include the effects of geometry, bathymetry and bottom roughness on mixing and circulation (Abdelrhman, 2005). The tidal prism methods consistently underestimate the exchange times and cannot predict the exchange rate of the deep isolated basin water and should be limited to estimating the exchange above the sill depth in fjord like systems (Gillibrand, 2001). The main and the deepest parts of Mulroy Bay, Kindrum and Broadwater are connected by a narrow area less than 200 meters wide and the water flux in this area shows clearly that water was flushed out and transported back to the areas increasing the water renewal. The channels and narrows are relatively shallow, which decreases their renewal time.

## 3.10 Conclusions.

Although the numerical modelling was challenging due to scarcity of information for 3D model parameterization, the model showed good agreement between prediction and measurement for the hydrodynamically complicated area of Mulroy Bay; a shallow fjordic system. Consequently, this model clearly has the potential to be successfully calibrated and used in similar situations in the future to study important issues concerning the hydrodynamic activity and water quality. In particular, it could be specifically adapted as a management tool for multiple aquaculture activities within complex bay systems. The barotropic flow is characterized by several eddies and the residual water velocities in this area show clearly that waters flushed out and in and are transported back to the areas and thus increase water renewal. In addition, the model has established the dominance of tidal-driven over wind driven circulation in the narrow areas and of wind driven flows in the inner areas. This study demonstrates the strong influences of wind forcing on the flushing characteristics of a hydrodynamically restricted system for which the tidal prism method is not appropriate

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# Chapter 4 Application of a 3D hydrodynamic model for sustainable marine finfish culture.

**Juan Moreno Navas, Trevor C Telfer and Lindsay G. Ross**

This chapter describes the use of the 3D hydrodynamic and particle tracking model developed and validated in chapert 3 to study the effects of mean current speed, quiescent water periods, stratification and bulk water circulation in Mulroy Bay. A series of surveys were carried out to measure salinity and temperature profiles in the study area during spring and summer 2007 and winter 2008. The hydrological parameters modelled have been extracted as an independent layers and incorporated into a GIS system. These environmental models can also be used to identify areas for appropriate site selection for salmon aquaculture and a Langangrian method will be used to simulate discharges from finfish cages to show the behaviour of waste in terms of water circulation and water exchange.

The main author, J Moreno Navas, conducted all field work and developed all sub models and final models. Prof Lindsay G Ross and Dr Trevor C Telfer provided supervisory and editorial support throughout the whole study.

The body of the text is presented as a publication-ready manuscript. This manuscript has been submitted to Continental Shelf Research an international journal dealing with the physical oceanography, sedimentology, geology, chemistry, biology and ecology of the shallow marine environment, from coastal and estuarine water out to the shelf break.

# Application of a 3D hydrodynamic model for sustainable marine finfish culture.

**Juan Moreno Navas (1), Trevor C Telfer and Lindsay G. Ross**

**4.1 Abstract.** Hydrographic conditions, in particular current speeds, have a strong influence on the management of fish cage culture. These hydrodynamic conditions can be used to predict particle movement within the water column and results used to optimize environmental conditions for effective site selection, setting of environmental quality standards, waste dispersion, and potential disease transfer. To this end, a 3D hydrodynamic model has been coupled to a particle tracking model to study the effects of mean current speed, quiescent water periods and bulk water circulation in Mulroy Bay, Co. Donegal Ireland, an Irish fjard (shallow fjordic system) important to the aquaculture industry. A Langangrian method simulated the instantaneous release of 6000 "particles" emulating discharge from finfish cages to show the behaviour of waste in terms of water circulation and water exchange.

The 3D spatial models developed were used to identify areas of mixed and stratified water using a version of the Simpson-Hunter criteria, and for appropriate site selection for salmon aquaculture.

The modelled outcomes for the stratification were in good agreement with the direct measurements of water column stratification based on observed density profiles. Calculations of the Simpson-Hunter tidal parameter indicated that most of Mulroy Bay was potentially stratified with a well mixed region over the shallow channels where the water is faster flowing.

The fjard was characterized by areas of both very low and high mean current speeds, with some areas having long periods of quiescent water. The residual current and the particle tracking animations created through the models revealed an anticlockwise eddy that may affect waste dispersion and potential for disease transfer from a major production area for Atlantic salmon culture, as it influences movement of water among cages and ensures that the retention time of waste substances from cages is extended.

The hydrodynamic model results were incorporated into the ArcView$^{TM}$ GIS system to provide an easy-to-use graphical interface for visualization and interrogation of results, and to allow input into wider ranging spatial modelling projects, such as coastal zone management systems and effective environmental management of fish cage aquaculture.

Key words: 3D hydrographic models, fish-cage waste dispersion, environmental management.

[1] Corresponding author: Institute of Aquaculture. University of Stirling. FK94LA. Stirling.UK (jmn1@stir.ac.uk) Tel: 01786767882 .Fax: 01786472133

## 4.2 Introduction.

Hydrographic conditions have an important influence on biological and physical processes related to marine aquaculture, including settlement and transport of larval molluscs or fish ectoparasites, rates of particle capture by suspension feeders, oxygen supply, influence on fish behaviour, growth and possibly flesh quality of cultivated molluscs and fishes, and transport and accumulation of soluble and particulate wastes released from the cultured organisms. Hydrographic measurement and use of this data in modelling water flow throughout coastal systems is becoming an important management tool for marine aquaculture.

The velocity profile of water currents depends on flow properties such as the Reynolds number (ratio of inertia to viscosity), turbulence, acceleration, fluid properties and boundary characteristics. Fjordic systems are considered regions of restricted exchange (RREs), and are often areas associated with settlement of humans due to fisheries, aquaculture, shipping and recreational activities. These activities have the potential to enhance any nutrient loading which may in turn increase the risk of eutrophication (Tett et al., 2003). Additional use of these water-based resources to expand existing or develop new aquaculture production will increase this risk further if not properly managed. Monitoring of the environment for this risk will only allow *post hoc* management after impact has occurred. Effective management requires predictive tools to model potential impacts and thus identify risks of aquaculture development or to locate its activities in order to minimise these impacts and to adopt best practice for development and regulation.

The physical environment and vertical mixing within fjordic systems has been extensively reviewed (Farmer and Freeland,1983; Freeland et al., 1980; Stigebrandt and Aure, 1989) along with wind/water interactions (Farmer, 1976; Farmer and Osborn, 1976; Dronkers and Zimmerman, 1982; Leth, 1995; Svendsen and Thompson, 1978). It is accepted that fjordic systems may be represented by a tripartite division within the water body: the near surface circulation zone, the intermediate zone between the surfaces and the sill, and the deep basins. In a wind-driven three layer system, for example, the residual current is in the direction of the wind-stress in the superficial layer, has mixed residual current directions in the intermediate layer, and has a return current in the deep basins.

The widely used tidal front model proposed by Simpson and Hunter (1974) identifies well-mixed and stratified regions separated by a boundary or front in which various combinations of tidal velocity and water depth produce mixed and stratified regions under constant heat flux. Its usefulness is that the buoyancy inputs are spatially uniform and the tides are the dominant energy source for vertical mixing, and consequently a tidal front plot is a useful indicator of the spatial distribution of tidal mixing. The potential energy of the water column is given by integrating the gravitational potential energy over the depth. The energy required to mix the water column thus increases with increasing stratification (Lee et al., 2005), with the potential energy contributors being heating or cooling across the water surface, the tides and the winds (Simpson and Bowers, 1981).

The production of finfish in cages causes a measurable impact on the quality of nearby water and seabed sediments due to ammonia excretion, depletion of available dissolved oxygen and release of faecal material and uneaten feed (Beveridge, 2004). The most severe impacts of marine fish cages have been associated with intensive aquaculture operations in areas with inadequate water circulation. The use of a hydrodynamic modelling approach in aquaculture planning regulation and monitoring was encouraged by Henderson et al. (2001). Such hydrodynamic models have been used in different salmon culture studies focused on different environmental problems such as nutrient waste, pesticide dispersion, oxygen depletion and dispersion of ectoparasite larvae (Table 4.1).

**Table 4.1. Summary of the use of hydrographic models in salmon culture in different countries and the environmental problems.**

| Author | Country | Software | Dimensions | Grid size ($m^2$) | Target |
|---|---|---|---|---|---|
| Falconer, A. and Hartnett, M.,1993. | Scotland | DIVAST | 2D | 200 | Nutrient , pesticide dispersion |
| Trites, R.W. and L. Petrie., 1995. | Canada | unknown | 2D | 100 | Oxygen depletion |
| Panchang et al., 1997. | USA | AWAST | 2D | 75 | Waste dispersion |
| Dudley, R.W.et al., 2000. | USA | AWAST | 2D | 30,75,150 | Waste dispersion |
| Greenberg et al., 2005. | Canada | QUODDY | 3D | 500 | Oxygen depletion |
| Murray,A.G. and Gillibrand.P.A., 2005. | Scotland | GF8 | 3D | 100 | Sea lice dispersion |
| Skogen et all, 2009 | Norway | NOWERCOM | 3D | 800 | Etrophication |

This study applied a 3D hydrodynamic and particle tracking model, MOHID, to predict water circulation and to map the main hydrological parameters that influence salmonid cage culture in a complex fjardic system with substantial aquaculture production (Mulroy Bay, Co Donegal, Ireland). The use of the model for investigation of sensitive and well flushed areas was investigated and the potential for such models in management and regulation of these sites was assessed.

## 4.3 Study area.

Mulroy Bay is a fjardic inlet (Fig 4.1), a glacially-derived embayment in low lying land situated on the northern coast of Co Donegal, Ireland (55 15’N , 7 45’W ). Mulroy Bay can be divided into four main areas: the Outer Bay, Northwater, Broadwater and the Channel. The latter is about 100-150 m wide and has three distinct sections; the First, Second and Third Narrows. Several areas within the Bay are licensed for Atlantic salmon farming with a production of approximately 800 to 900 tonnes per annum over the last five to ten years.

Maximum depths within the Bay are 47m in Northwater and 40 m in Broadwater. Most of Northwater and the northern half of Broadwater is deeper than 20m, with most of the

Channel, the Outer Bay and the southern half of Broadwater being less than 10 m deep with significant areas less than 5m deep. The area between 0m to 10m is approximately 62 % of the total, 10m to 20m is 28 % and 20m to 47m is 10 %.

Wind speed data from 2005 indicated a mean speed of 6.8 m/s (at Malin Head), predominantly from a south-westerly direction (180°-270°), though on occasion wind directions were highly variable. The tidal range varies from 3.2 to 4.2 m (neap to spring) at the Bar at the mouth of the Outer Bay to 1.2 to 1.6 m in Broadwater. The tidal stream was very strong in the three Narrows sections, and there is some delay in turnover of water from the inner to outer bays illustrated by 143 minutes difference between high water at the mouth and Broadwater (Parkes, 1958) .

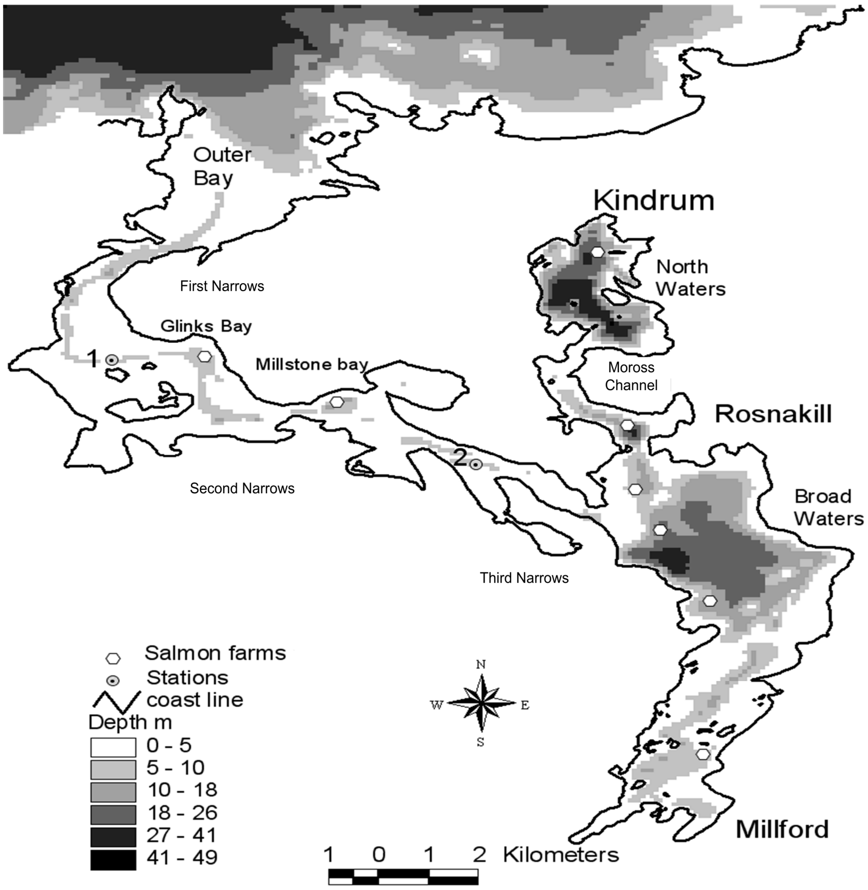

**Figure 4.1. The location and bathymetry of the study area, Mulroy bay, off Ireland's north coast.The positions of the salmon cages are shown as white circles and the two hydrological stations (1,2).**

The general flow circulation is characterized by several eddies, and a clearly wind driven scenario. The system can be considered as three layers, with a residual current in the direction of the wind stress in the superficial layer, a return current in the deep parts of the bay and mixed residual current directions in the mid-water layer. Moreno et al., (unpublished) modelled the residual velocities and showed clearly that waters flushed in and out were transported back to the fjard increasing the water renewal and also demonstrated the strong influences of wind forcing on the circulation patterns and the flushing characteristics of this restricted area.

## 4.4 Field sampling and data collection.

Hydrographic measurements were taken at two stations within Mulroy Bay (Fig. 4.1) using two Valeport BFM 308 Direct Recording current meters deployed at 2 meters below the surface and 2 meters above the seabed. Deployment was for 16 days from the 8th to 24th February 2005 during which current speed (m/s), direction (degrees magN) and water pressure (dB) were recorded at 20 minute intervals over a 60 s averaging period. For comparison of the quiescent period, only, an additional data set was used which was collected between 13th to 28th September 2000 at three different stations within the area (Institute of Aquaculture, unpublished data).

A series of surveys were carried out in the study area during spring and summer 2007 and winter 2008. Salinity and temperature profiles were taken at 1 m depth intervals at 7 stations (Fig 4. 2) in order to characterize and compare differences in the study area. Temperature readings were taken using a WTW portable oxygen meter. Salinity was measured using an Oxi 197, LF 196 conductivity meter and probe. Each probe was connected to the meter using 100 m of pressure resistant armoured cable. The density was calculated as a function of temperature, salinity and pressure (Fofonoff and

Millard, 1983). Delta Sigma -T $\left(\Delta\sigma_t\right)$ was calculated by the density differences between superficial and bottom values.

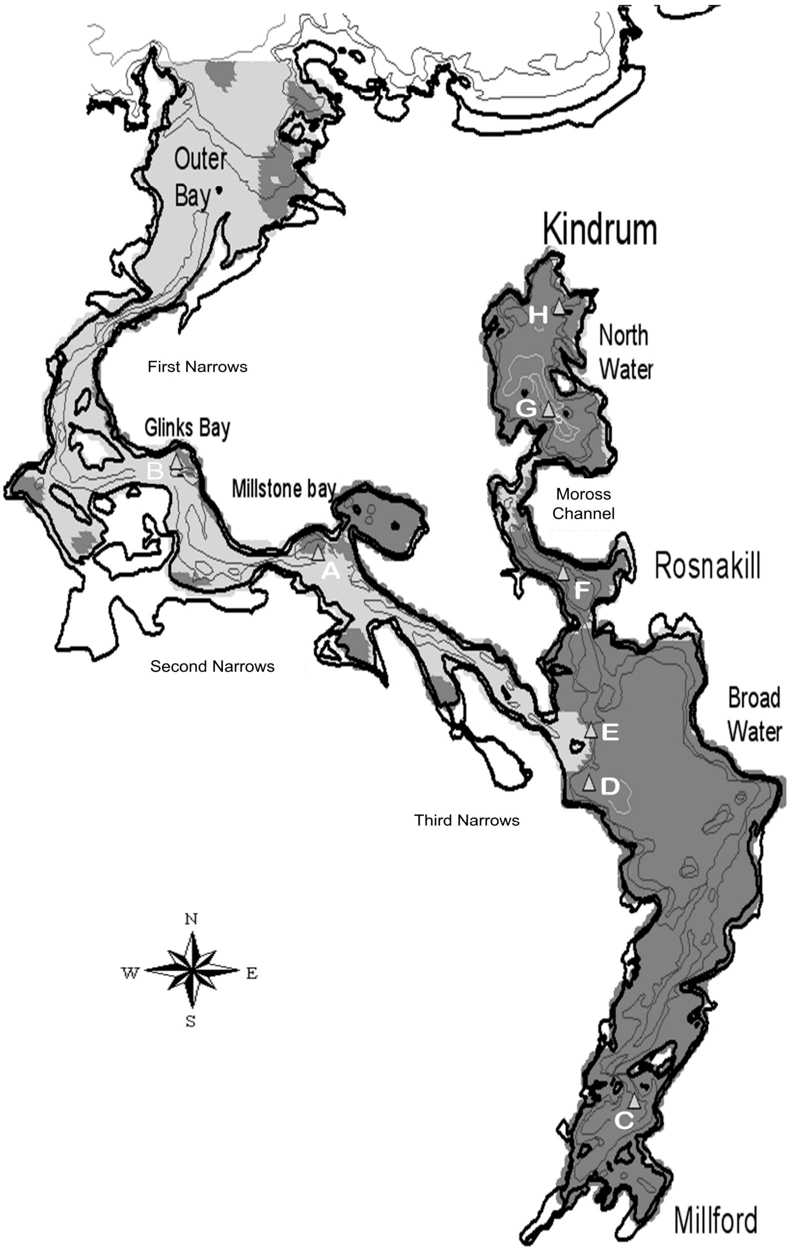

**Figure 4.2. Distribution of Hunter-Simpson stratification criteria in Mulroy Bay, showing the mixed areas as light grey (values <1), stratified as dark grey (values >2) and the sampling stations (A to H) used.**

## 4.5 The three-dimensional (3D) water modeling system, MOHID.

The hydrodynamic model MOHID 3D used in this work (Martins et al., 1998; Martins et al., 2001; Santos, 1995) solves the equations of a three-dimensional flow for incompressible fluids and an equation of state relating density to salinity and temperature. The MOHID model has been applied to several coastal and estuarine areas and it has shown its ability to simulate complex features of the flows. It has been used, for example, in coastal circulation, nutrient loads and residence time models in several places around the world (see http://www.mohid.com/Publications/JP.asp).

Following Martins et al. (2001), the Cartesian coordinate framework equations are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial u_1}{\partial t} + \frac{\partial (u_j u_1)}{\partial x_j} = -fu_2 - g\frac{\rho_\eta}{\rho_0}\frac{\partial \eta}{\partial x_1} - \frac{1}{\rho_0}\frac{\partial p_S}{\partial x_1} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_1} dx_3 + \frac{\partial}{\partial x_j}\left(\mathrm{A}_j \frac{\partial u_1}{\partial x_j}\right) \qquad (2)$$

$$\frac{\partial u_2}{\partial t} + \frac{\partial (u_j u_2)}{\partial x_j} = fu_1 - g\frac{\rho_\eta}{\rho_0}\frac{\partial \eta}{\partial x_2} - \frac{1}{\rho_0}\frac{\partial p_S}{\partial x_2} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_2} dx_3 + \frac{\partial}{\partial x_j}\left(\mathrm{A}_j \frac{\partial u_2}{\partial x_j}\right) \qquad (3)$$

$$\frac{\partial p}{\partial x_3} = -\rho g \qquad (4)$$

Where $(u_i)$ are the velocity components $x_i$, $\eta$ is the free surface elevation, $\mathrm{A}_i$ turbulent viscosity coefficients. $f$ is the Coriolis parameter. $p_s$ the atmospheric pressure $g$ is the gravitational acceleration. $\rho$ is the density and $\rho'$ its anomaly.

The density is calculated as a function of salinity and temperature by the equation of state, (Leendertsse and Liu, 1978).

A bathymetry model was obtained by digitizing from Admiralty Chart (SNC 2699) to produce initial vector data followed by interpolation to a 50 m grid resolution. An Arakawa C grid was used for spatial discretization (Arakawa and Lamb, 1977). The MOHID model allows several options for vertical discretization: Cartesian coordinates, sigma coordinates or a generic vertical coordinate. In this study a sigma coordinate was chosen with 5 vertical layers. The temporal discretization is carried out by means of a semi implicit ADI (Alternate Direction Implicit) algorithm, introduced by Peaceman and Racford in 1955 (Fletcher, 1991).

Bottom stress was parameterized using a quadratic law, by calculating the bottom drag coefficient, *Cd*, from the expression:

$$Cd = \left( \frac{K}{\ln\left( \dfrac{z + z_0^b}{z_0^b} \right)} \right)^2 \quad (5)$$

Where $K$ is the Von Karman constant, $z$ observation length and $z_0^b$ is the bottom roughness length.

Vertical eddy viscosity/diffusivity was determined with a turbulence closure model selected from those available in the General Ocean Turbulence Model GOTM (Burchard et al., 1999).

In this application a 3D model forced with both tide and wind was implemented. At the boundary the water level taken from the FES2004 global tide solution is imposed (Lyard et al., 2006). Wind was assumed equal in all domains to that measured by the closest meteorological station. The parameters used in the model calculations are summarized in Table 4.2.

**Table 4.2. Parameters used in the calculations.**

| Physical parameter | Numerical value | |
|---|---|---|
| Time step: | 2s | |
| Grid mesh: | 50m | |
| Horizontal cells (x,y): | 193, 244 | |
| Vertical coordinate: | Sigma | |
| Vertical layers: | 5 | |
| Horizontal Eddy Viscosity: | 0.407738 | $m^2 s^{-1}$ |
| Vertical Eddy viscosity: | 0.001 | $m^2 s^{-1}$ |
| Drag coefficient: | 0.03 | |
| Wind rugosity coefficient: | 0.0025 | |
| River discharge: | No | |
| Temperature: | 7. ° C | |
| Salinity: | 32.6 psu | |

The residual current $u_e$ was estimated by averaging the horizontal flow $u$ over a complete time period $T$:

$$u_e = 1/T \int_0^T u dt \qquad (6)$$

A particle tracking model was coupled to the hydrodynamic model to describe the movement of the passive tracers.

The particle tracking assumed that the velocity of each particle ($u_P$) can be split into a large scale organized flow, characterized by a mean velocity ($u_M$), provided by the model, and a smaller scale random fluctuation ($u_F$) such as $u_P = u_M + u_F$.

The particle tracking model used the equation:

$$\frac{\partial x_i}{\partial t} = u_i\left(x_i, t\right) \quad (7)$$

Where $u_i$ is the mean velocity and $x_i$ the particle position, this equation is solved using an explicit method:

$$x_i^{t+\Delta t} = x_i^t + \Delta t u_i^t \quad (8)$$

Random movement was calculated following the procedure of (Allen, 1982) in which random displacement was calculated using the mixing length and the turbulent velocity standard deviation provided by the hydrodynamic model.

For the validation process the relative mean absolute error (RMAE) and the Index of Agreement, (IoAd) were computed using equations 9 and 10 respectively. The RMAE has been used by several authors to the evaluate numerical model results (Fernandes et al., 2001; Sousa and Dias, 2007; Sutherland et al., 2004) and is given by:

$$RMAE = \frac{\left\langle \left| Q_m - Q_c \right| \right\rangle}{\left\langle \left| Q_m \right| \right\rangle} \quad (9)$$

where $Q_m$ and $Q_c$ are the measured and computed velocity vector respectively.

The preliminary classification of RMAE ranges suggested by (Walstra et al., 2001) is shown in Table 4.3.

**Table 4.3. Classifications error for RMAE (after Walstra et al., 2001).**

| Classification | RMAE |
|---|---|
| Excellent | < 0.2 |
| Good | 0.2-0.4 |
| Reasonable | 0.4-0.7 |
| Poor | 0.7-1 |
| Bad | >1 |

The index of agreement measure, (IoAd) ( Dawson et al., 2007; Wilmott,1981) is given by:

$$IoAd = 1 - \frac{\sum_{i=1}^{n}\left(Q_m - Q_c\right)^2}{\sum_{i=1}^{n}\left(\left|Q_c - \overline{Q_i}\right| + \left|Q_m - \overline{Q_i}\right|\right)^2} \quad (10)$$

where $Q_m$ and $Q_c$ is the measured and computed velocity vector respectively

and $\overline{Q_i}$ is a mean velocity vector measured, the best results are when IoAd close to 1. The IoAd has been used to evaluate numerical model results by Sousa and Dias (2007) and Warner et al. (2005).

Stratification was quantified by determining the potential energy anomaly, $\varphi$ , following Simpson et al. (1978) and Simpson and Bowers (1981) using the equation:

$$\varphi = \frac{g}{H}\int_{-H}^{0}\left(\rho^{-} - \rho(z)\right)z\,dz \quad (11)$$

where the z coordinate is positive vertically upwards from the sea surface, g is the gravitational acceleration $\bar{\rho}$ is the mean density and H the water column height.

The Hunter Simpson stratification parameter (Simpson and Hunter, 1974) is given by:

$$S = \log_{10}\left[\frac{h}{\left|U^3\right|}\right] \quad (12)$$

where, S is the stratification parameter, h the water depth, and U is the magnitude of the instantaneous tidal stream velocity over one tidal cycle. The stratification parameter was calculated with h as the mean water depth for each cell and U as a mean tidal velocity modelled for each grid position. Although the Hunter Simpson stratification parameter was selected, it must be assumed that the stratification was only caused by thermal heat.

The value of S at 1.5 indicates the presence of a front. Values of S < 1 indicate well mixed regions and S >2 well stratified areas (Perry et al., 1983). To verify the existence of well mixed and stratified zones the surface stratification was calculated, defined as the difference in Delta Sigma -T $\left(\Delta\sigma_t\right)$ between the surface and the bottom densities following Perry et al. (1983) and Muelbert et al. (1994) ..The energy required to mix the water column thus increases with increasing stratification, so in mixed waters it is < 10 $Jm^{-3}$, in frontal waters 10-20 $Jm^{-3}$, and in stratified waters >20 $Jm^{-3}$ (Lee et al., 2005).

The quiescent period was given by the percentage incidence of current speeds within the range 0-3cm/s (SEPA, 2005), and was obtained from the modelled numerical values. To obtain the residence time, a modification of the approach of Braunschweig et al. (2003) was used, in which the six fish production cage-blocks were considered as boxes either 100 x 150 meters or 100 x 200m in area. These boxes are used as the release points for the Lagrangian tracers (1000 particles in each box simulating cages, 6000 in total) and the movement of these tracers throughout the fjard system was examined. The time period simulated was based on the worst case, represented by a day with neap tides and the initial model running in the flood tide period without wind. The hydrodynamic model results were incorporated into the Arc View GIS system in order to provide an easy-to-use graphical user interface for visualization, interrogation of results and as an input to a further spatial modelling project.

## 4.6 Results.

### 4.6.1 Field data.

Mean seasonal temperature ranged from 6ºC in February 2008, to 12ºC in April 2007 to 16ºC in August 2007. In the summer (16ºC) and winter (6ºC) seasons there was complete thermal vertical mixing with the same values of temperature in the water column in the whole study area. The density profile (Fig. 4.3) shows that during the spring period, April 2007, several stations showed stratified patterns (stations C, D, G, H) mainly due to differences between superficial and bottom values of 1.6ºC maximum in Kindrum and 1ºC in the Milford area. No variation was observed at the sampling stations at Glinsk and Millstone (stations A and B respectively) in the Narrows.

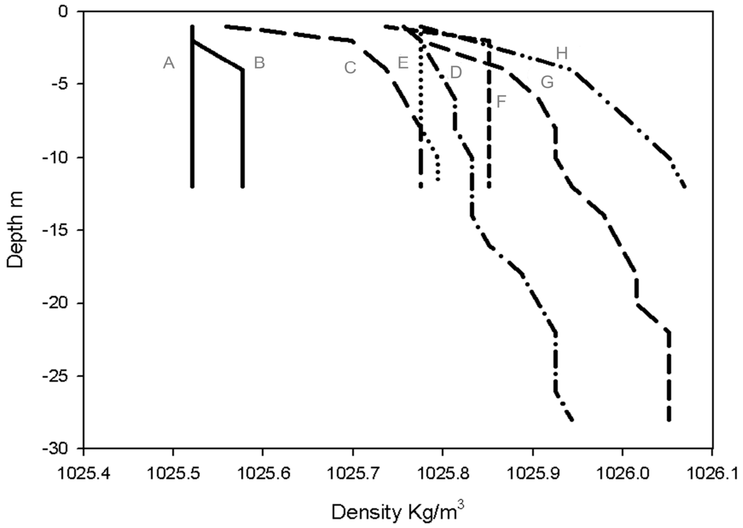

**Figure 4.3. Density variation with depth from all stations for April 2007.**

The salinity during the summer and winter seasons was completely vertically mixed with the same values throughout the water column. Seasonal salinity values fluctuated from 30.9 psu in January to 34.0 in August. The values at several stations over the whole area were very similar for summer and winter periods (sampled in February 2008 and August 2007) both at the surface and the seabed with little variation occurring between stations. Salinity depth profiles obtained in February 2008 (Fig. 4.4) indicated that there were different values in the different areas of the fjard, 30.9 to 31.0 in Kindrum area, possibly caused by rain and small rivers draining into the area, while elsewhere within the Broadwater values were close to 32.6.

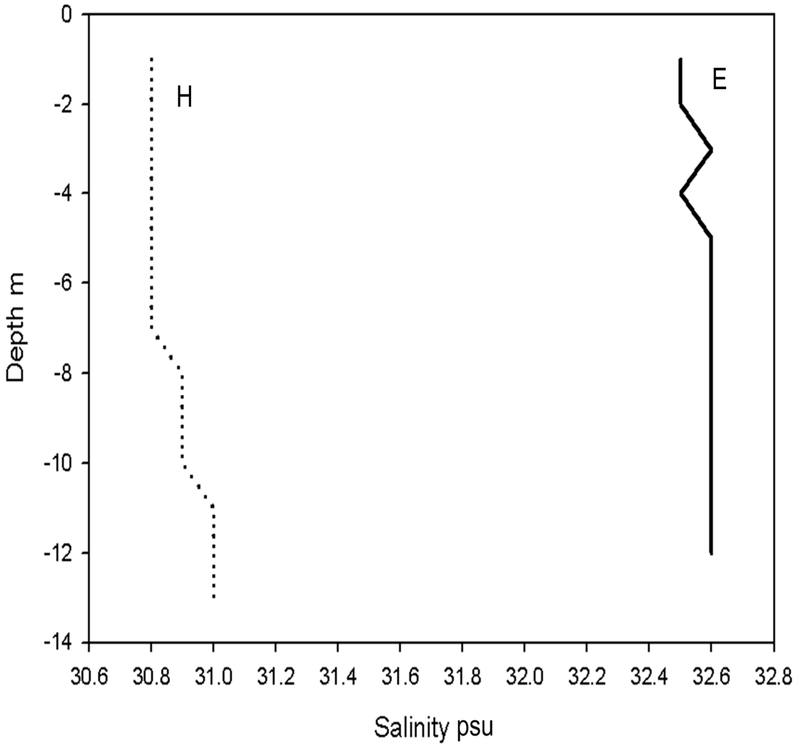

**Figure 4.4. Examples of salinity vs. bottom-depth plot from the stations H and E illustrated the difference in salinity between zones in winter season.**

In spring time the Delta Sigma T $\left(\Delta\sigma_t\right)$ at the Narrows stations A and B and Station D were less than 0.056 $kgm^{-3}$ units, whereas at Broadwater and Kindrum stations (H,G,E,C) there was more stratification with values greater than 0.110 $kgm^{-3}$, the maximum values 0.295 $kgm^{-3}$ being in the Kindrum area. The potential energy at the narrows station (Station A,B,C) was almost zero, between 0 and 0.95 $Jm^{-3}$ , while in Broadwater, Moross channel and Kindrum values were between the maximum in Kindrum zone with 13.47$Jm^{-3}$ and the minimum of 1.038 $Jm^{-3}$ in Moross channel.

### 4.6.2 Modelled results.

In this study, the 3D hydrodynamic model was based on a 15 day lunar tidal cycle with forcing by a real wind data set. A mathematical sigma coordinate was used with 5 vertical layers; the first layer was the bottom and the fifth at the surface. The sensitivity analysis showed that the variation in the eddy viscosity did not have a large influence on the modelling outcomes, while the drag coefficient has the highest relative sensitivity (see chapter 3). The hydrodynamic measurements used to validate the model were carried out in Mulroy Bay between 15 to 24 /02/05 (9 days in total).

For sea surface elevation (Fig 4.5), the calculated values of IoAd were close to 1 and low values of RMAE revealed a good agreement between the prediction of the model and the observations (Fig 4.5 and Table 4.4) according to Walstra et al. (2001). The values of the observed and modelled mean current velocity (Fig 4.5), at station 1, were similar with differences of 0.015 m/s at the surface and 0.035 m/s near the seabed. At station 2 the differences in mean modelled current velocity was higher, being 0.084 m/s at the surface and 0.088 m/s near the seabed between observed and modelled values.

**Table 4.4. RMAE, and IoAd for the eastward (U) and northward (V) velocities, current intensity at the superficial (s) and the bottom (b) and the tidal surface elevation for the stations**

| Parameter | Station 1 | | Station 2 | |
|---|---|---|---|---|
| | RMAE | IoAd | RMAE | IoAd |
| | | | | |
| Us | 0.008 | 0.971 | 0.3 | 0.960 |
| Vs | 0.54 | 0.341 | 0.05 | 0.980 |
| Ub | 0.05 | 0.976 | 0.39 | 0.929 |
| Vb | 0.28 | 0.620 | 0.18 | 0.937 |
| Current intensity s | | 0.903 | | 0.903 |
| Current intensity b | | 0.896 | | 0.762 |
| Elevation | 0.025 | 0.950 | 0.057 | 0.927 |

The current directions were almost identical at both stations (Fig. 4.5), showing that the model can predict the current direction accurately.

At station 1 the model agreed well with the eastward velocity measurements (Table 4.4) in the surface and bottom layers, with IoAd values close to 1 and low values of RMAE (Table 4.4) which were within the excellent category according to Walstra et al. (2001). The northward velocity results were more complicated. The RMAE values were 0.28 and 0.54 for bottom and superficial levels, respectively, with IoAd values varying from 0.341 to 0.62 (Table 4.4). The model did not predict this velocity component accurately although it did provide very good approximation of current speed and current direction and the northward velocity influences may be low.

At station 2 the model agreed well with the northward and eastward velocities measured at the surface and the bottom, with IoAd values close to 1 and excellent and good values of RMAE (see Table 4.4).

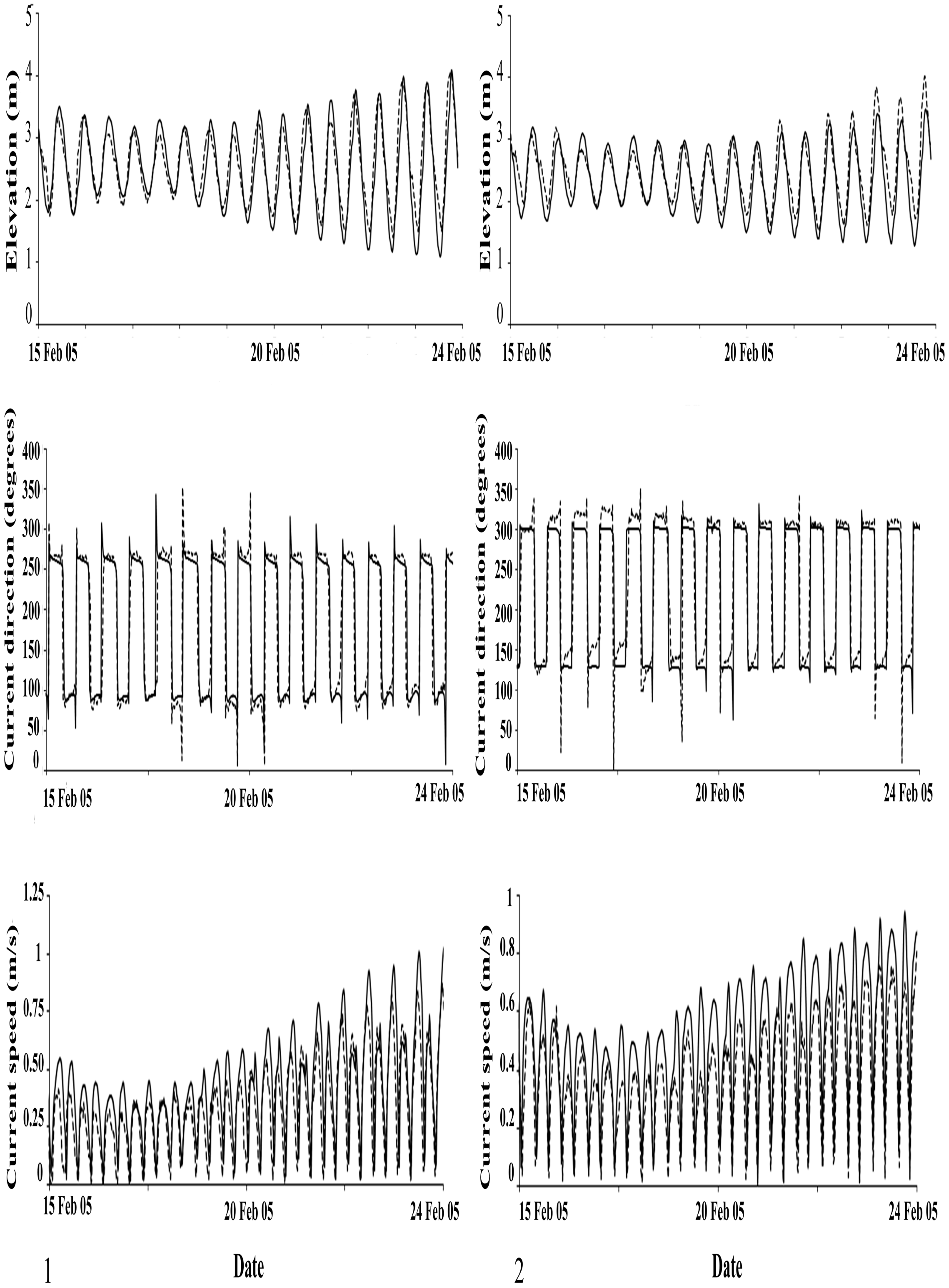

**Figure 4.5. Time series of the elevation, current direction and current intensity in Mulroy Bay measured (dotted and dark line) and modelled (grey line) at the two stations 1 and 2. Values of RMAE and IoAd are given in Table 4.4.**

The average measured current speeds were used for the 4th layer within the model as this gave the best estimation of the cage environment, as it approximated the depth of the mid and bottom of the cages, where the majority of the waste originates (Corner et al., 2006) The mean current speed modelled in this layer is given in (Fig. 4.6), from which two regions can be differentiated; 1) the Narrows, where modelled mean current speeds ranged from 0.2 m/s to more than 1 m/s., and 2) Broadwater, where the modelled mean current speeds ranged between 0.03 m/s at Kindrum to 0.2 m/s within the Morross channel.

**Figure 4.6. Distribution of modelled mean current speed in Mulroy bay. The data shown is the current speed (m/s) in layer 4 which approximates cage positions in the water column.**

The quiescent period, defined as percentage of the tidal period where current speeds were less than 0.03 m/s (SEPA, 2005), were given for the first layer (bottom), as this provided an approximation of the seabed environment (Fig. 4.7). The quiescent period in this layer ranged from 10% to 80% of the tidal period. Areas of Kindrum and Milford were considered mostly quiescent, in contrast to the well flushed and only minimally quiescent areas within the Narrows and Moross Channel (defined according to criteria set by SEPA, 2005). The modelled and measured quiescent periods at the two stations at the surface and bottom were very similar at about 1 % (Table 4.5).

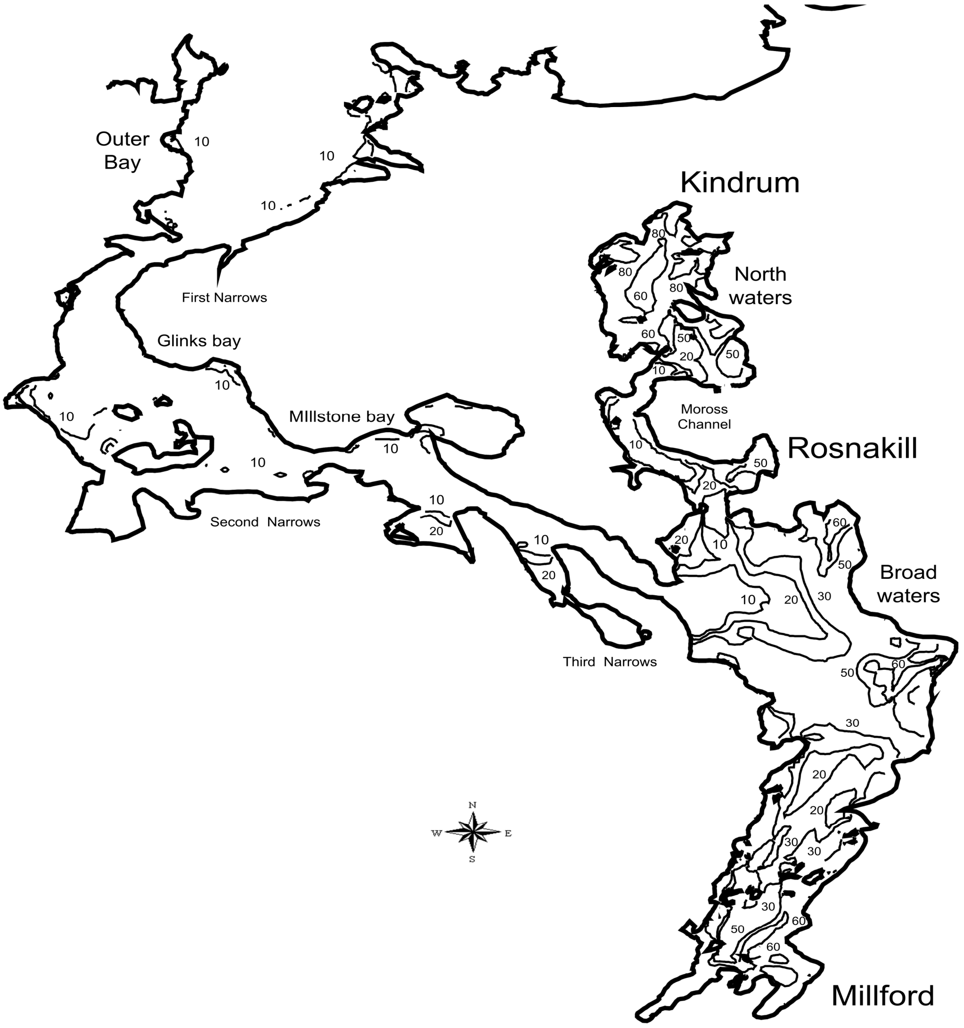

**Figure 4.7. Distribution of the modeled percentage of quiescent period in Mulroy Bay. The data shown is the quiescent period in layer 1 which approximates the bottom environment.**

Comparing the modeled result with the hydrographic data set from 2000 but with the same time period (15 days) that include the locations of three fish cages, it can be seen that in Broadwater differences are in order of less than 10 %, with 25 % at Kindrum and 10 % at Moross .

**Table 4.5. Quiescent period at the surface (S) and the bottom (B) for stations 1 and 2, and three cage sites, showing the data set used.**

| Station | Data set | Quiescent Period | | | |
|---|---|---|---|---|---|
| | | Measured S | Measured B | Modelled S | Modelled B |
| Station 1 | Feb 2005 | 1% | 1% | 1% | 1% |
| Station 2 | Feb 2005 | 1% | Nr | 1% | 1% |
| Broadwater | Sep 2000 | 10% | 25% | 17% | 20% |
| Kindrum | Sep 2000 | 95% | 99% | 98% | 75% |
| Moross | Sep 2000 | 16% | 30% | 10% | 20% |

nr = not measured due to current meter failure

The modelled residual currents (Fig. 4.8) show a circulation structure with an anticlockwise eddy in the Millstone area where the maximum salmon production is located. At the Narrows the 3D hydrodynamic model showed the same patterns in the top, medium and bottom layers which are similar due to the low depth.

To illustrate the mixing of the volume of water (simulating effluents) from the cages, the particles in different cages positions were colour-coded. The particles were then advected by the model flow field for one day (17/2/2005). The results are presented as an animated dispersion model (Animation 6). The animation clearly shows the current eddy, at certain times of the tide, in the Millstone area and mixing water from the Glinsk (colour red) and Millstone (colour yellow).

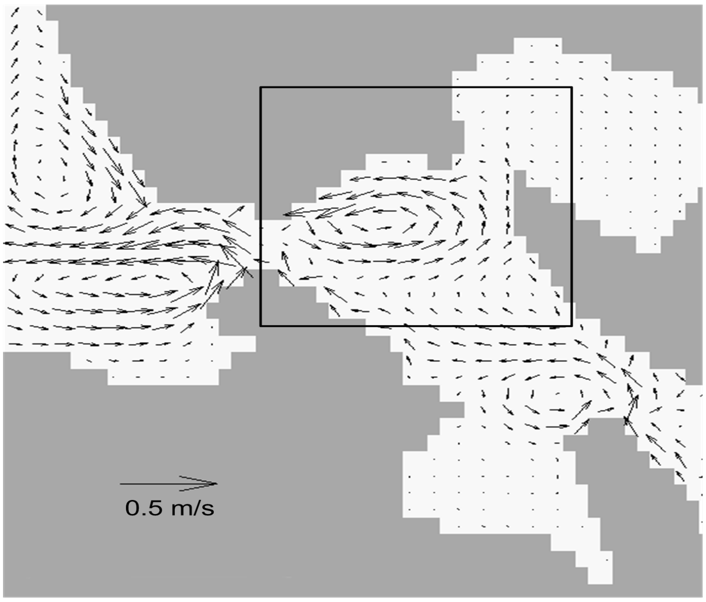

**Figure 4.8. Distribution of residual current in the central sections of Mulroy Bay. A very clear circulation structure can be indentified with anticlockwise and a clockwise eddies in different areas of the narrows. In Millstone area an anticlockwise eddy (black square) may affected the cage water exchange**

The water from Glinsk is eventually flushed away to the Broadwater area, while in Millstone part is flushed to Broadwater and the rest remains to feed the eddy. Particles originating from fish farms in the inner bays (Moross in green and Broadwater in blue) exhibited small changes at the beginning of the model run but by the end the volume of particles are dispersed so that the Broadwater particles end up in the mouth and in Moross Channel while Moross Channel particles area are spread throughout the channel.

The distribution of the modelled Hunter Simpson criteria can be separated into two areas (Fig. 4.2). The narrows, Glinsk, Millstone and the northern part of the Moross Channel are considered well mixed, with values less than 1 for the Hunter-Simpson criteria while the remainder of Mulroy Bay can be considered as stratified with modelled Hunter-Simpson criteria values of greater than 2.

## 4.7 Discussion.

Numerical circulation models can provide a practical solution to the problem of coastal mixing (Wildish et al., 2004) and water exchange in Regions of Restricted Exchange that host important industries, such as aquaculture, and can improve resolution of the combined effects of tidal and wind-driven forcing as well as reflecting complex topography and intertidal drying zones (Hargrave, 2003). The 3D modeling schemes require intensive computer resources and may suffer from computational instability problems, but the models can provide a complete spatial and temporal dataset on water currents for the entire computational domain. 2D models will provide vertical and depth averaged components of velocity (speed and direction) but this information is insufficient in some cases, particularly when the differences between the surface and the bottom velocities may differ considerably. In addition, the 2D approach does not provide differential information for near seabed environments such as the extended quiescent period. Panchang et al. (1997) suggest that the vertical variations in the current speed are likely to affect the dispersion of waste and resuspension of settled wastes and a 3D approach would therefore be more appropriate for modeling such wastes.

The study area on which the present work is based is characterized by two main hydrographic areas that could host aquaculture sites; a highly energetic and well flushed part of the fjard in the narrows and a low energy, poorly flushed part in the Broadwater, Kindrum and Millford areas. The results indicate that the area follows a seasonal cycle that contains three contrasting regimes. In the summer and winter the systems show complete thermal vertical mixing while in spring the inner bay system is stratified but the more hydrodynamic Narrows area is always well mixed. Similar hydrological behaviour was encountered in a Scottish fjord (Rippeth et al., 1995). The measured values for temperature and salinity are in good agreement with those directly measured in Mulroy Bay by other authors (C-Mar, 2000; Nunn, 1996;Telfer and Robinson, 2003). The temperature is highest (16-17ºC) and the oxygen concentration is lowest, close to 7 mg/l, in summer time.

The model has been forced by tides and winds. C- Mar (2000) found a direct relationship between wind forcing and the concentration of dissolved oxygen in the water and the increase of water exchange with the ocean. The numerical model could provide important insight by showing how the fjard would respond to a considerable increment in the temperature, changing wind direction and intensity scenarios and dissolved oxygen evolution, so providing the possibility of modelling climate-related "what-if" scenarios in advance.

Cross (1993) suggested that net cage locations must consider circulation dynamics, including the evaluation of back eddy and mass transport contribution to waste dispersion for a site. Brooks and Churchill (1991) noticed that finer grid resolution (less than 100m) is important for characterization of the circulation in coastal areas similar to Mulroy Bay, and Panchang et al. (1997) suggested the use of a fine (75m) grid size in areas with aquaculture activities. The latter modelled the presence of an eddy which inhibited the exit of salmon waste.

Hargrave et al. (1995) note that most studies in aquaculture have shown that the local extent of altered benthic community structure and biomass is limited to less than 50 m from the edge of the cages and for this reason the model was parameterized to this horizontal resolution.

Residual current velocity and the developed animation show the presence of an eddy in the largest fish production area in Millstone which may affect environmental quality by retaining rather than dispersing waste. This is the first animated example of how a physical circulation structure could affect different aquaculture sites. It is clearly important to consider the inter-relationship among them and to be able to identify such areas for environmental management because nutrient, waste dispersion, and potential disease transfers from the cages may affect the other sites.

The general flow circulation in Mulroy Bay is characterized by several eddies, which are clearly wind driven (Moreno et al, unpublished). The tidal range varies from the Bar in the Outer Bay (3.2-4.2 m) to Broadwater (1.2-1.6m), and tidal streams are very strong, particularly in the Narrows which have the lowest quiescent values and maximum mean current speeds. Hargrave et al. (1995) noticed that benthic variables which are correlated with organic matter sedimentation can be used to scale the degree of organic enrichment. However, the author suggested that biological processes are not always sufficient to limit organic matter accumulation especially in areas where hydrographic conditions and/or low current speeds result in low rates of oxygen supply to the sediment surface. A 3D scheme could provide much improved spatial and temporal information about the conditions in the sea bed.

The modelled periods of quiescent water and mean current speed were confirmed as reasonably accurate by comparison with measurements of hydrographic conditions at different locations within Mulroy Bay, and even comparing hydrographic data sets from different time periods that include the locations of the three fish cages sites. It is important to note that although the times modeled were almost the same 15 day tidal lunar cycle the different wind conditions could affect the result. Water quality measurements from Telfer and Robinson (2003) showed that the areas with the lowest values of oxygen in deep water coincide with areas with the highest values of quiescent water (Kindrum and Milford). C- Mar (2000) reported high values of sediment oxygen demand in the area, and the quiescent period may be a good modelled indicator of potential oxygen depletion in the sea bed.

In strongly stratified marine systems, dissolved material can be effectively trapped in the upper or lower parts of the water column. In an aquaculture context, stratification can be an important factor in the dispersal of organic matter from certain farms in the inner portions of fjords (Wildish et al., 2004). A slight thermal stratification was observed in the spring period during this study. A thermal stratification was observed in Northwater and Broadwater, (C-Mar, 2000; Minchin, 1981) and in the southern region at Milford. Although there are no large rivers draining into the bay to significantly affect salinity, a shallow halocline can develop in parts of Northwater and Broadwater where water from land runoff lies on the surface during calmer weather. Salinity depth profiles obtained in January 1999 (C-Mar, 2000) indicated that there was saline stratification in the southern region of Broadwater, probably caused by land runoff and streams which drain into this area.

The modelled Hunter-Simpson tidal stratification parameter indicated that most of Mulroy Bay was potentially stratified in spring time with well mixed areas in the shallow narrows. The values are in good agreement with the direct measurements of water column stratification based on observed density profiles. In terms of potential energy, where the sigma value is low and potential energy is close to zero the Hunter-Simpson criterion is below 2. Stations with highest values of Delta Sigma-T and potential energy have the highest values of the Hunter-Simpson criteria with values more than 2.

Simpson and Hunter (1974) used the surface current amplitude at springs, whereas in this study the mean surface current speed of a lunar tidal cycle was used. This provided a better cage site approximation but produced lower values of current speed which could lead to higher values of the Hunter-Simpson criteria. Several stratification parameters have been defined by other authors but Hunter and Sharp (1983) noticed that, at a given site, all could be approximately related to each other. Lu et al. (2001) used only four tidal constituents: M2, S2, K1 and O1, and found that the resulting modeled stratification distributions did not change significantly in comparison to modeled results given by Pingree and Griffiths (1980) who used only one constituent, M2. In the present study, both elevation and current data were generated and included more tidal constituents from the FES2004 model, M2, S2, N2, K2, K1, O1, Q1, P1 and M4. No significant changes of stratification parameter distribution were expected.

The Hunter-Simpson stratification criteria was selected for its simplicity and ease of calculation. It was used to model the worse possible scenario where the stratification was only caused by thermal heat. The area has no influences from river discharge affecting the stratification and other important energy sources for the water mixing of the water column, such as wind mixing and tidal stirring, are not taken into account. A strong wind blowing for many hours and high turbulence from the bottom can produce a mixed layer and reduce the density differences.

The results from the hydrodynamic model can be incorporated into GIS to provide an easy-to-use graphical user interface for 2D, 3D and temporal visualization, for interrogation of results and as an input to other spatial models. This offers the possibility of combining the data with layers of spatial information about economic and social aspects, communications and security of the study area to develop an integrated ecological approach to aquaculture activities. As described by Henderson et al. (2001) the main potential and recommendation for using modelling in aquaculture activities is as an indicator of environmental change, as a strong descriptor of physical processes, as a tool for best practices in development and regulations, as a cost effective alternative to extensive field's studies, and to provide fast predictions of potential impacts for different aquaculture scenarios. In addition, the hydrodynamic and water quality models could be useful in the assessment of the mixing zone and in designating allowable zones of effect for nutrient and chemical discharges. However, any modelling process may give false or inaccurate predictions and thus there are risks in applying modelling approaches to any decision making process, where complex environmental processes are oversimplified (Henderson et al., 2001). The process of 3D circulation modelling is expensive; however the benefits of such a decision support tool which is well tuned for aquaculture development are also considerable (Andréfout et al., 2006).

## 4.8 Conclusion.

Hydrographic conditions play an important role in several environmental processes related to aquaculture. Knowledge of local hydrography is thus fundamental in any decision making process. The production of finfish in cages causes a measurable impact on the surrounding water and seabed due to excreted soluble nutrients, faeces production and uneaten feed. The most severe environmental impact and management problems have been associated with intensive operations in areas with inadequate water circulation. 3D hydrodynamic modelling coupled to particle tracking modelling provides spatially explicit information on the key variables governing the dynamics of marine coastal areas and the transport and fate of pollutants in the near and far field cage marine environment. Its integrative approach and analytical capabilities is a powerful tool to guide effectively the environmental management of marine aquaculture. It can provide information on environmental sensitivity through mapping hydrographic characteristics using important parameters, such as, current speed, stratification index, quiescent periods, water circulation, exchange and renewal. This is particularly important in the areas that host intensive aquaculture activities. The use of modelling approaches in aquaculture planning regulation and monitoring should be encouraged.

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# Chapter 5 Modelling environmental vulnerability of finfish aquaculture using GIS-based neuro fuzzy techniques.

**Authors: J. Moreno [1] T. Telfer and L.G. Ross.**

This chapter describes the neuro-fuzzy techniques used in a GIS to predict coastal vulnerability for marine cage aquaculture. The hydrological parameters calculated in Chapter 3 and 4 have been incorporated as an independent layers into a GIS system. Sediment samples for measurement of nitrogen content and granulometry were collected by grab at eight fish production and several sites between 2002 and 2006

The main author, J Moreno Navas, conducted all field work and developed all sub-models and final models. Prof Lindsay G Ross and Dr Trevor C Telfer provided supervisory and editorial support throughout the whole study.

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# Modelling environmental vulnerability of finfish aquaculture using GIS-based neuro fuzzy techniques.

**Juan Moreno Navas[1], Trevor C Telfer and Lindsay G. Ross**

**5.1 Abstract.** The aim of this study was to develop a predictive model of coastal vulnerability to marine aquaculture using neuro-fuzzy techniques in a Geographic Information System (GIS) framework. Combination of GIS with a robust neuro-fuzzy modeling approach has the advantage that expert scientific knowledge in coastal aquaculture activities can be incorporated into the fuzzy neural network to "train" models to enhance accuracy of the output. Here we utilize an adaptive neuro-fuzzy system to classify vulnerable areas of the environment in a complex coastal scenario within Mulroy Bay, a fjard in Co Donegal Ireland, which is host to a number of different aquaculture activities. Data on the physical environment and aquaculture suitability were derived from a 3-dimensional hydrodynamic model (3DMOHID) and GIS (Arc View 3.2) for incorporation into the final model framework and included mean and maximum current velocities, current flow quiescence time, water column stratification, sediment granulometry, particulate waste dispersion distance, oxygen depletion, water depth, coastal protection zones, and slope.

Environmental vulnerability models, based on neuro-fuzzy techniques, showed sensitivity to the membership shapes of the fuzzy sets, the nature of the weightings applied to the model rules, and validation techniques used during the learning and validation process. The overall training had an accuracy of 85.71%, with a Kappa coefficient of agreement of 81%. The unclassified GIS cells ranged from 0% to 24.18%. A statistical comparison between vulnerability scores and a significant product of aquaculture waste (nitrogen concentrations in sediment under the salmon cages) showed that the final model gave a good correlation between predicted environmental vulnerability and sediment nitrogen levels, highlighting a number of areas in Mulroy Bay of variable sensitivity to aquaculture.

The neurofuzzy technique for GIS modeling can appropriately classify coastal regions into areas of different levels of environmental vulnerability to a range of aquaculture activities. This is therefore a useful tool for identifying locations where such activities have a higher risk of contaminating the marine environment in relation to other coastal activities. Such a model can be used to facilitate policy decision for aquaculture site selection.

Key words: Neuro-fuzzy techniques, environmental vulnerability, Geographic Information Systems, marine cage aquaculture, aquaculture site selection.

[1] Corresponding author

## 5.2 Introduction.

Recent improvements in the capabilities of Geographic Information Systems (GIS) have enabled their increasing use as tools for decision-making and policy formulation. The ability to store, manipulate and model using spatial data has meant that GIS has an important application in many sectors, including Integrated Coastal Zone Management and management of marine resources. There is considerable opportunity to develop new modelling techniques within the GIS framework to classify and assess the suitability of coastal areas for development of sustainable marine cage culture. However, locational data sets are often uncertain and incomplete, therefore new models employing “soft computing” methods such as  fuzzy logic may be more suitable (Zadeh, 1965). Nauck et al. (1997) defined “soft computing” as taking into account approaches to human reasoning and tolerance for incompleteness, uncertainty, imprecision and fuzziness in decision making processes”. To date, the use of this approach for resolving coastal environmental problems has clearly been underutilised.

Fuzzy data sets naturally lend themselves to modelling uncertainty in vague and ambiguous conditions. The approach has been applied to problems where domain knowledge is abundant but numerical data have been difficult to obtain (Abe, 2001). In particular, neuro-fuzzy systems have been applied in various and different domains e.g. control, data analysis and decision support.

Many types of ecological and environmental data are qualitative or use discrete categories (Silvert, 1997) and combinations of quantitative and qualitative data, so are difficult to incorporate into environmental modelling and classification schemes which produce numerical indices of environmental quality. The use of fuzzy data sets provides a consistent method for incorporating ambiguous quantitative and non-quantitative data into ecological studies. For example, ambiguous or fuzzy geographical boundaries can be used between areas when the following criteria (Jacquez et al., 2000) are present: 1) Continuousness: when boundaries and thresholds are difficult to assess because the measurements of an entity produce a gradient (e.g. polluted areas); 2) Ambiguity: where boundaries are defined and tied to linguistic descriptions or parameters (e.g. “High”, “Low” levels).

Fuzzy logic methodology has been used in several instances to study the marine environment, such as for marine eutrophication (Urbanski, 1999), water pollution (Pimpas et al., 1999), benthic faunal community mapping (Meaille and Wald, 1990), vulnerability of marine areas to scuba diving and marine fishes to fishing (Di Franco et al., 2009; Cheung et al., 2005) and assessing impacts of marine fish farming (Angel et al., 1998). In the latter case, the scoring methodology used fuzzy classification systems to quantify changes in benthic macrofauna under fish farms over time. A fuzzy logic method was also applied to an inventory of aquaculture suitability (Field, 2001) and for aquaculture site selection for planning, for strategic assessment and site selections (Zeng and Zhou, 2001). SimCoast is a "fuzzy logic", rule-based, expert system in which a combination of fuzzy logic has been used to produce a soft intelligence system for multi-objective decision-making (Anon, 1999). It is designed to enable researchers, managers, and decision-makers to create and evaluate different policy scenarios for coastal zone management. (Wood and Dragicevic, 2007) examined the applicability of an integrated spatial decision support framework based on GIS, multi-criteria evaluation (MCE) and fuzzy sets to objectively identify priority locations for future marine protection.

A neuro-fuzzy system is a fuzzy system that is trained by either a learning algorithm, such as neural network theory, or by using specific examples for initial learning or enhanced learning (Nauck and Kruse, 1999). A neuro-classifier is a fuzzy classifier obtained by a learning procedure, which is used when interpretation and the employment of prior knowledge is required (Nauck and Kruse, 1999) .

Neuro-fuzzy techniques can learn a system’s behaviour from sufficiently large data sets and automatically generate fuzzy rules and fuzzy sets to a predefined level of accuracy (Dixon, 2005). Neuro-fuzzy methods, pattern classifications and their comparison are discussed in detail by Nauck et al. (1997) and Abe (2001). Neuro-fuzzy methodology has also been used within GIS to determine suitable sites for the locations of public golf courses (Purvis et al., 1999), modelling ground-water vulnerability (Dixon, 2005), soil erosion assessment (Zhu et al., 2009) and for irrigation water needs mapping (Valdes et al., 2003). Zheng and Kainz (1999) discussed an adaptive neural network based on a fuzzy inference system that was able to learn fuzzy sets and fuzzy rules from GIS for decision making.

Environmental vulnerability is concerned with the risk of damage to the natural environment. Due to its complex nature, vulnerability theory has been developed to provide a framework for logical development and measurement (Kaly et al., 2002). Marine environmental vulnerability is the susceptibility of sea- and transitional water resources to pollution by various activities and contaminants.

In the early 1990s the United States Environmental Protection Agency (USEPA) attempted to distinguish between the sensitivity of single aquifers and their relationship to the overall vulnerability to contamination of an area's ground water resources. In contrast, vulnerability combines the hydrodynamic and topographic characteristics to determine sensitivity of "human" vulnerability factors by addressing specific coastal uses, management practices, and/or contaminant properties from aquaculture activities. The present study has attempted to adapt this concept to an aquaculture framework, by investigating the relative ease with which an aquaculture contaminant applied on or near the coast could affect the zone of interest based exclusively upon hydrodynamic and topographic factors, which is a function solely of the intrinsic characteristics of the zone in question.

The aim of this study was to develop a classification using neuro-fuzzy techniques in a GIS framework to predict coastal environmental vulnerability for marine cage aquaculture.

## 5.3 Study area.

Mulroy Bay is a fjardic inlet situated on the northern coast of Co Donegal, Ireland (Long. $7^{o}$ 45’W, Lat. $55^{o}$ 15’N) (Fig. 5.1). It is bounded on the west by the Rosguill Peninsula and on the east by Fanad Peninsula (Fig 5.1). It is a convoluted and complex environment, extending inland for about 19 km with a range of hydrodynamic conditions. Although it is a proposed Special Area of Conservation (SAC), aquaculture is intensively practiced within the bay, with up to 16 operators currently licensed for mussel, oyster, clam, scallop, abalone and Atlantic salmon production. Production of Atlantic salmon within Mulroy Bay and Lough Swilly is approximately 3500 tonnes per annum (Bermingham and Mulcahy 2007) and considerable increases have occurred in shellfish production from around 20 to 800 tonnes in two decades (C-Mar, 2000).

There are three main types of protected areas designation in Mulroy Bay: Special Areas of Conservation SAC, Special Protection Areas, (SPA), and proposed Natural Heritage Areas (NHA) (http://www.npws.ie/en/MapsData/). The bay is divided into four main geographical areas: the Outer Bay, Northwater, Broadwater and the Narrows. The Narrows is further sub-divided into three sections each approximately 100-150 m wide, known as First, Second and Third Narrows. The tidal range varies from the Bar at the mouth of the Outer Bay (3.2 - 4.2 m) to Broadwater (1.2 - 1.6m), tidal streams vary considerably within the bay being very strong in the Narrows and weak in Broadwater and at Kindrum (Northwater). There is a delay of 2 hours and 23 minutes between the time of high water at the Bar and the southern end of Broadwater (Parkes, 1958). No large rivers drain into the bay meaning there is little significant affect of freshwater inflow on salinity.

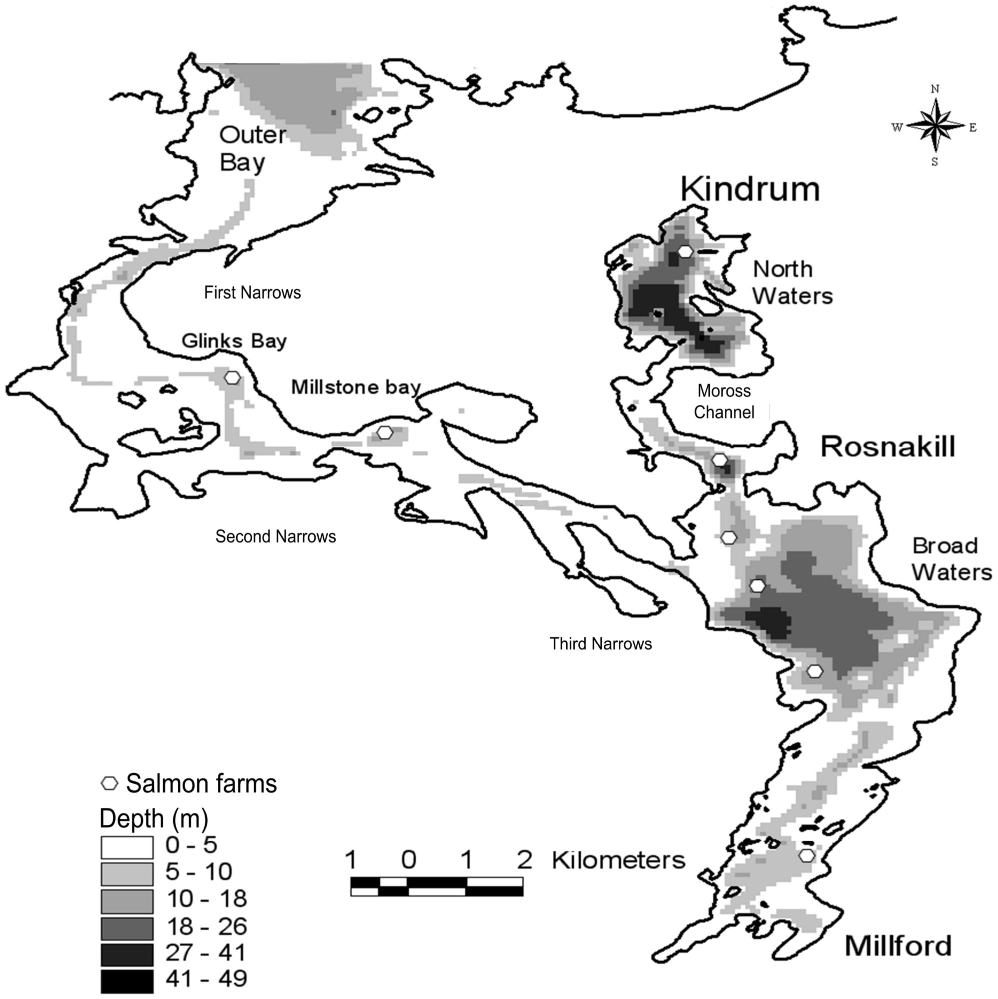

**Figure 5.1. The study area in Mulroy bay off Ireland's north coast showing the positions of licensed salmon cages (white dots).**

The general circulation flow is clearly influenced by wind driven currents, particularly within the inner bay, and characterized by several current eddies. As a result, the flow systems can be considered as three layers; a superficial (upper) layer where the residual current is in the direction of the wind stress, a bottom layer consisting of a return current and a medium (middle) layer where mixed residual current directions occur. The water circulation is characterized by several eddies and the residual water velocities in this area show clearly that waters flushed out and in and are transported back to the areas and thus increase water renewal (Moreno et al., unpublished).

Water temperature varies seasonally from 6ºC in February (measured in 2008), to 12ºC in April (2007) to 16ºC in August (2007). In summer (~16ºC) and winter (~6ºC) the waters within the study area are normally vertically well mixed. However, thermal stratification was observed in Northwater and Broadwater (Minchin, 1981; C-Mar, 2000) and in the southern reaches of the bay near Milford (Telfer and Robinson 2003).

## 5.4 Methods.

Several initial data inputs were required for model development, including information about hydrodynamic and marine environmental parameters. These primary data were either collected as cartographic reference data, hydrographic and bathymetric data and GPS positions of the finfish cages, or were derived directly from these data. The secondary layers (see Fig. 5.2), physical environmental parameters and suitability parameters were derived from the hydrodynamic model and the GIS models. In the processing phase, a 3D hydrodynamic model provided spatially explicit information on the key variables governing the dynamics of marine coastal areas and the transport and fate of pollutants. This was calibrated and validated using *in situ* data and, along with other environmental models (waste dispersion and oxygen depletion), is coupled with a GIS (ArcView$^{TM}$ ver 3.2, ESRI) to predict the evolution of the environmental parameters and to allow simulation of a number of "what if" scenarios. The final outputs, are in the form of GIS-based neuro fuzzy layers which show environmental vulnerability. Fig. 5.2 outlines the relationships of these layers.

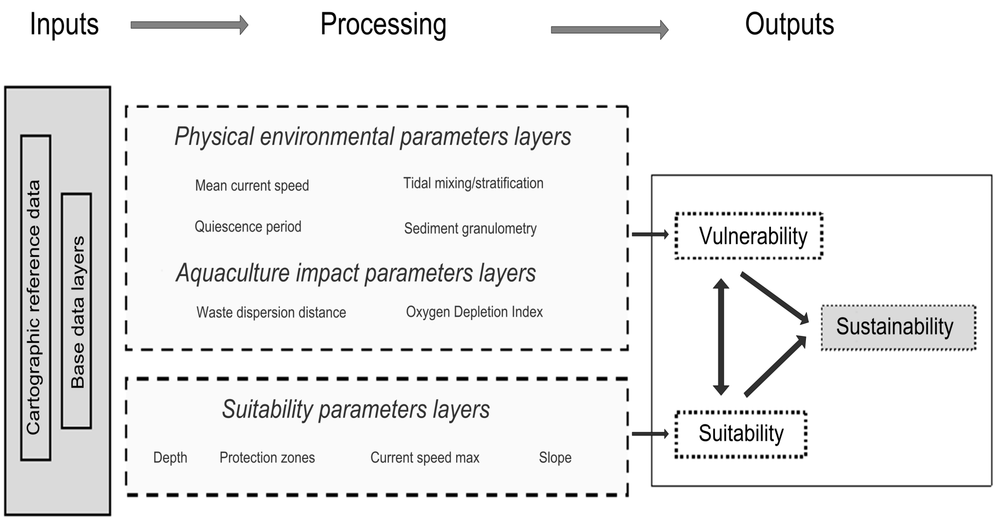

**Figure 5.2. Data and process linkages within the suitability and vulnerability model.**

The simultaneous consideration of suitability and vulnerability, can conceptually define sustainability as having maximum coastal suitability for aquaculture but minimum coastal vulnerability. The output is a spatial environmental model applied to coastal areas intended to facilitate policy decisions, taking into account the intrinsic characteristics of the target area.

The first stage in the neuro-fuzzy analysis was construction of a spatial database for the study area taking into account potential environmental effects which contribute to vulnerability. Several information layers were indentified for this purpose:

### 5.4.1 Bathymetry.

The bathymetry was digitized from the Admiralty Chart and from this data a bathymetric model was developed by interpolation to a 50 m grid resolution (Fig 5.1).

### 5.4.2 Mean current velocity.

Current velocity is an indicator of potential sensitivity to impacts from fish farming (Carroll et al., 2003) and an indication of a site’s hydrographic and environmental characteristics (SEPA, 2005). The current velocity was derived from a 3-dimensional hydrodynamic model, (Moreno et al., unpublished)

### 5.4.3 Quiescence time.

The percentage incidence of current velocities within the range 0-3cm/s may be used as a further indication of a site's hydrographic and environmental characteristics (SEPA, 2005). The quiescence time was derived from a 3-dimensional hydrodynamic model, (Moreno et al., unpublished)

### 5.4.4 Granulometry.

This provides basic information on sediment composition and is important for the determination of oxygen and nutrient exchange between sediment and water column (Viaroli et al., 2004). Seabed sediment sampling for granulometric analysis was carried out in August 2007 using a hand operated Van Veen grab (sample area 0.025 $m^2$) at 30 randomly assigned locations throughout the bay system. A sub-sample of sediment was taken from each grab and stored frozen ($-20\pm1^{o}C$) until laboratory analysis by dry sieving (Folk, 1974). The maximum velocities from hydrodynamic simulations using the 3D hydrodynamic model MOHID, (Moreno et al., unpublished) were plotted against the mean grain diameters for each sampling location to give a linear regression model of the relationship, enabling modeled current velocity over the whole system to be used as a proxy for sediment type

### 5.4.5 Predicted particulate waste dispersion.

The particulate effluents from a fish farm, consisting of excess feed from the fish, will be dispersed and for a large part will settle under or near to the farm. Where and how much will settle depends on the amount and disintegration of the effluent, the sinking velocity of the particles, the current velocity and the water depth. The predicted dispersion distance of particulate waste from the fish cages (uneaten feed) was determined using a simple waste dispersion model, based on the equation of (Gowen and Bradbury, 1987) for estimating horizontal pellet dispersion.

### 5.4.6 Oxygen Depletion Index.

This index, developed by Page et al., (2005), is the time required for the fish biomass to reduce the ambient concentration of oxygen to a specified threshold level in the absence of water renewal within the fish cage or farm. Dissolved oxygen (DO) levels were measured at fish farms in the Moross Channel, at Millstone and in the Broadwater, during the one summer (July 2007). DO was recorded (±0.3 mg/l; YSI Instruments, Y550A, Y58) over two 5 min sampling periods from a location situated downstream of the main current direction from the fish cages. This gave a worst case scenario for DO influence by fish production.

The oxygen depletion index (ODI) (Page et al., 2005) is calculated by the ratio of the time necessary for the salmon biomass to reduce the ambient concentration of dissolved oxygen to a specified threshold level in the absence of flushing $\tau_{thres}$ to the time needed to flush the cage or farm $\tau_{fl}$.

$$ODI = \frac{\tau_{thres}}{\tau_{fl}} \quad \text{(Eq 1)}$$

When the value is much less than 1, it means that the salmon are able to reduce dissolved oxygen to a threshold value in less time than oxygen can be replenished by flushing within the cage.

The $\tau_{thres}$ is calculated as:

$$\tau_{thres} = \frac{C_0 - C_{thres}}{R} \quad \text{(Eq 2)}$$

Where R is the respiration rate of the fish per unit volume of water within the cage, $C_0$ is the ambient concentration of dissolve oxygen away from the cage and $C_{thres}$ is the minimum concentration of dissolve oxygen that is desired within the cage.

$\tau_{fl}$ is therefore calculated as L/U where L is the diameter of a cage, and U is the typical water velocity in the area.

In this study the ODI was calculated for a representative single salmon cage using an oxygen concentration threshold of 6 mg/l , an ambient level of 7 mg/l, a 25 m diameter cage, pre-market fish of 4 kg biomass with a swimming velocity of 1 body length per second, a stocking density of 5 fish per $m^3$ (20 $kg/m^3$) and water temperature of 16ºC. The respiration rate for a non-feeding fish is approximately 111mg $O_2$/kg/h and the methodology of Grottum and Sigholt (1998) was used to estimate the specific oxygen consumption rate by salmon. A worst case scenario was adopted by assuming a 50% reduction of the current velocity due to bio-fouling, no reduction in DO was assumed either due to feeding or oxygen demand associated with waste and bio-fouling.

### 5.4.7 Stratification Index.

In strongly stratified marine systems, dissolved material can effectively be trapped in the upper or lower parts of the water column. The Hunter-Simpson stratification parameter (Simpson and Hunter, 1974) was used to represent this and is given by:

$$S = \log_{10}\left[\frac{h}{\left|U^3\right|}\right] \quad \text{(Eq 3)}$$

where, S is the stratification parameter, h the water depth (m) and U is the magnitude of the instantaneous tidal stream velocity over one tidal cycle (m/s). The stratification parameter was calculated for h as the mean water depth for each 50 x 50 m grid cell and U as a mean tidal velocity modelled for each grid position. A value of S = 1.5 indicates the presence of a front, values of S < 1 indicates well mixed regions and S >2 shows highly stratified areas, (Perry et al., 1983).

### 5.4.8 GIS layers and suitability derivation.

All data collected for classification of environmental parameters were not interpolated as layers consisting of 50 x 50 m grid cells. All grid layers were incorporated into a GIS framework (Arc view 3.2 ESRI). The combination of the layers, depth, slope, maximum current velocity and protected areas enabled the apparent suitability of an area to be assessed according to the criteria of Perez (2003) and Beveridge (2004). The GIS was used to filter and extract areas of < 10 m depth, more than 14 degrees of bathymetric slope, a maximum current velocity >1 m/s and within protected areas, from the data set. Following this process, the remaining cells were classified using the neuro fuzzy classifiers.

### 5.4.9 Neuro-Fuzzy Systems.

In this study the neuro-fuzzy software NEFCLASS-J for JAVA platforms (NEuro Fuzzy CLASSifier, (see: http://fuzzy.cs.uni-magdeburg.de/nefclass/ ) was used (Nauck and Kruse, 1999). The neuro-fuzzy classification model NEFCLASS –J, offers learning algorithms to create the structure (rule base) and the parameters (fuzzy sets) of a fuzzy classifier from a set of labeled data (training sites) to create interpretable classifiers. The software applies a fuzzy variant of the back propagation algorithm to tune the characteristic parameters of the fuzzy membership functions. It is also possible to use fuzzy systems for classifications with rules such as; if $\chi_1$ is $\mu_1$ and $\chi_2$ is $\mu_2$ and…. $\chi_n$

is $\mu_n$ then pattern ($\chi_1, \chi_2 \ldots, \chi_n$). In this case cell 1, cell 2, cell n from the GIS, belongs to class i, where the $\mu_1 \ldots, \mu_n$ are fuzzy sets (low, medium, high environmental vulnerability fuzzy sets).

NEFCLASS architecture, ( Fig 5.3), has a three-layer fuzzy perceptron in which the first layer, $\chi_n$, consists of input neurons, the second layer, Rn, of hidden neurons and the third layer, Cn, of output neurons. The hidden layer neurons represent the fuzzy rules and the output layer neurons the different environmental vulnerability classes of the classification problem with one output neuron per class. After an observation has been propagated through the network, its predicted class is assigned according to the output neuron with the highest activation value on a winner-takes-all basis.

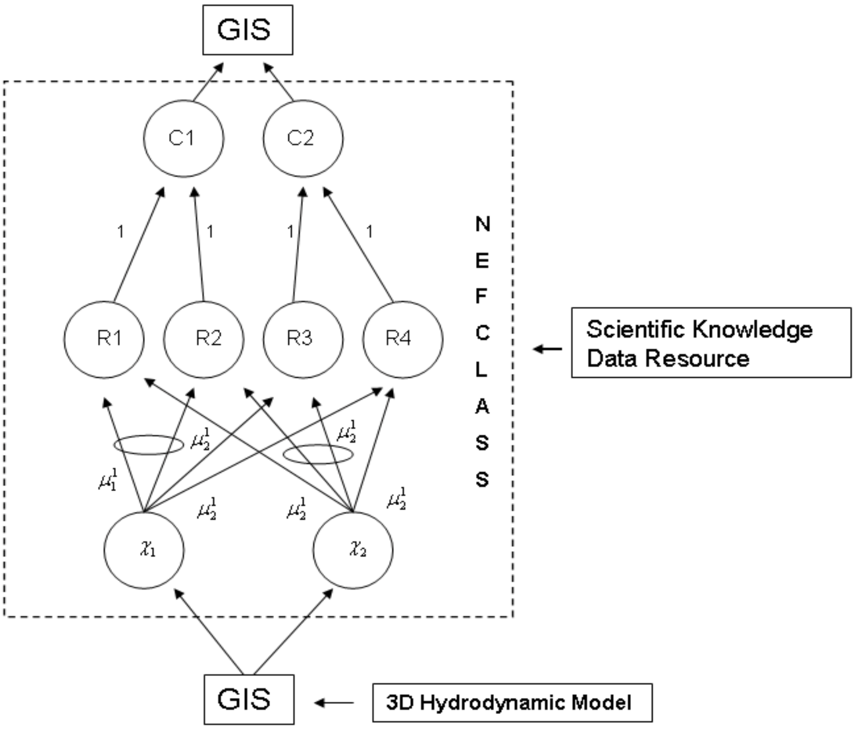

**Figure 5.3. An idealized data flow of the GIS /3DHydrodynamic model integration, the classification scene and the NEFCLASS program architecture with three layers feedforward neural network.**

The neuro-fuzzy systems needs several initial data inputs (Fig 5.3) and these were provided from a 3D hydrodynamic model calibrated and validated using *in situ* data distribution, coupled with a GIS. Independent learning and validation data sets were extracted from the study area layers using the GIS.

Fuzzy sets are defined by membership functions and rule bases and the shapes of the fuzzy sets are defined by the membership functions (Fig. 5.4) which are a representation of a linguistic variable to a fuzzy set as a matter of degree. Two types of membership functions allow realistic representation of the environmental parameters, trapezoidal and bell membership shapes. We selected the classifier with the highest accuracy and the lowest values of misclassification of cells for the total spatial domain.

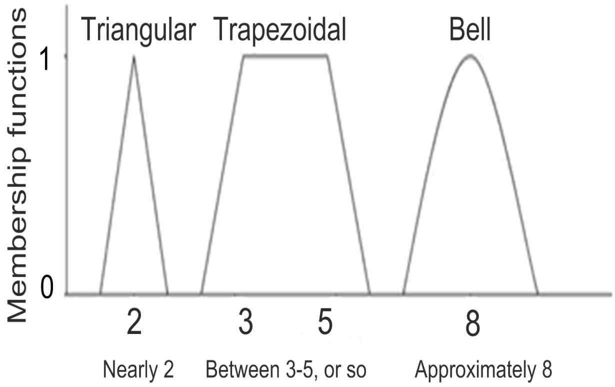

**Figure 5.4 .Types of fuzzy membership functions.**

### 5.4.10 Sensitivity analysis.

Sensitivity analysis was used to investigate how the model responded to changes in the inputs and the different configuration of the software provided. In order to assess the sensitivity of neuro-fuzzy model (the number and the shape of the fuzzy sets), validation methods and rule weights were varied over 16 different runs covering all the possibilities that the NEFCLASSS program provided.

### 5.4.11 Training of neuro-fuzzy classifiers.

Training sites with mostly different hydrodynamic characteristics were selected using stratified random sampling in different geographical areas of the study area. A total of 42 training sites were sampled from the GIS raster data layers, and the vulnerability categories for each were manually classified into four categories based on expert opinions from focus group meetings and interviews (Table 5.1). For simplicity and clarity for the experts the training sites table was developed using both numerical and text values, although only the numerical values were used in the neuro-fuzzy classification. A total of 6 experts, with more than 15 years research and academic experience in environmental management of salmonid culture and 2 years aquaculture industry experience, were used. A descriptive statistics (minimum, maximum, mean, standard deviation) of every classifier category for some of the environmental vulnerability parameters used was also calculated.

The classification performance was evaluated by the recognition rate, *R*, given by

$$R = \frac{100M_c}{M}(\%) \quad \text{(Eq 3)}$$

Where Mc is the number of correctly classified data and M is the number of classified data (Abe, 2001). The kappa coefficient of agreement, (Congalton and Mead, 1983), a discrete multivariate technique, was used in the classifier accuracy assessment.

The final results from NEFCLASS were imported into Arc View providing an easy-to use graphical user interface for visualization, interrogation of results and as an input to a further spatial modelling project.

**Table 5.1. Examples of training sites used for the classifier and the final classification by the experts in aquaculture activities.**

| **Depth** (m) | **Average** (m/s) | **Quiescent** % | **Bottom type** | **Stratification** | **ODI** | **Dispellet** (m) | **High Vulnerability** | **Medium/High Vulnerability** | **Medium/Low Vulnerability** | **Low Vulnerability** |
|---|---|---|---|---|---|---|---|---|---|---|
| 28.43 | 0.01 | 72 | fine sand | HIGH | YES | 2.75 | X | | | |
| 11.35 | 0.09 | 7 | medium sand | HIGH | NO | 4.53 | | | x | |
| 10.02 | 0.03 | 93 | fine sand | HIGH | NO | 0.71 | X | | | |
| 10.31 | 0.02 | 42 | medium sand | HIGH | YES | 1.66 | X | | | |
| 24.69 | 0.03 | 41 | medium sand | HIGH | NO | 4.36 | | X | | |
| 30.35 | 0.02 | 48 | medium sand | HIGH | YES | 4.72 | | X | | |
| 37.64 | 0.02 | 58 | medium sand | HIGH | YES | 5.14 | X | | | |
| 19.86 | 0.13 | 7 | coarse sand | HIGH | NO | 10.41 | | | | X |
| 16.17 | 0.07 | 18 | medium sand | HIGH | NO | 4.62 | | | X | |
| 11.12 | 0.41 | 2 | very coarse sand | NO | NO | 18.17 | | | | X |

As an indicator of the overall predictive performance of the model, seabed total nitrogen percentages were compared among sites classified into different environmental vulnerability categories.

Sediment samples for measurement of nitrogen content were collected by grab (0.025 $m^2$) at eight fish production sites between 2002 and 2006. Each year, triplicate samples were taken from beneath the centre of each cage block and at the downstream end of each cage block. Samples were transported as frozen and, after thawing, were oven dried overnight at 90 $^{o}$C. Nitrogen content was analysed as percentage by dry weight of sediment using a Perkin Elmer 2400 Series ii CHNS/O analyser.

Seabed total nitrogen percentages were square-root transformed and analyzed using a non-parametric method (Kruskal-Wallis' test). Follow-up tests were conducted to evaluate pairwise differences among the four categories, controlling for Type I errors across tests by using the Bonferroni approach. The pairwise comparisons were made using the Mann-Whitney U test, as the data did not follow the assumptions of normality and homogeneity of variances as determined by Shapiro-Wilks and Bartlett's test, respectively (Sokal and Rohlf, 1981). Spearman's rank correlation coefficient was calculated between percentage seabed nitrogen and vulnerability categories to assess trends in the data. A similar statistical methology as that used by Lake et al. (2003) was used to assess the predictive performace of a GIS model. The analyses were performed in SPSS 13.0 Statistical Package for Social Sciences (SPSS Inc., Chicago, USA).

## 5.5 Results.

### 5.5.1 Hydrodynamic characteristics.

The predicted maximum dispersion distance (Fig 5.5a) for feed pellets shows that the channels and the Narrows, are the highest dispersive areas with 10 to 20 meters settlement from the cage edges. However, the majority of the Bay system had a low dispersive distance of less than 4 m from the cage edges.

The mean current velocities (Fig. 5.5b) ranged between 0.03 $m.s^{-1}$ in areas such as Kindrum (Northwater) and Milford (Broadwater) to > 1 $m.s^{-1}$ in the second Narrows. In the less dynamic areas within Broadwater and Northwater water currents were between 0.03 and 0.1 $m.s^{-1}$, whereas throughout the Narrows and in Moross Channel water currents were mostly between 0.1 and 0.5 $m.s^{-1}$.

Modelled stratification for the bay indicated by the Hunter-Simpson criteria (Fig. 5.5c) shows that the two areas of fastest current flow and least quiescence, the Narrows and Moross Channel, are considered well mixed with values of < 2 whereas the rest of Mulroy Bay was more stratified with values of >2.

Percentage time of quiescent waters modelled for the bottom (seabed) water column layer (Fig. 5.5d) provided an indication of dynamic conditions at the sediment interface. The quiescent periods at the seabed were shown to range between 20 to 80% through the bay. Again, the less dynamic areas of Broadwater and Northwater were also the most quiescent.

The maximum simulated current velocity, for specific locations within Mulroy Bay, against the mean sediment grain diameter shows a significant correlation ($R^2 = 0.70$; $p < 0.001$). The sediment distribution layer (Fig. 5.6a) shows that the areas affected by high currents, the channels and the proximity of the third narrows, are covered by stones, gravel and coarse sand while, the rest is dominated by medium/fine sand areas. The areas with lowest currents such as Kindrum and Millford are characterized by very fine grain sediments.

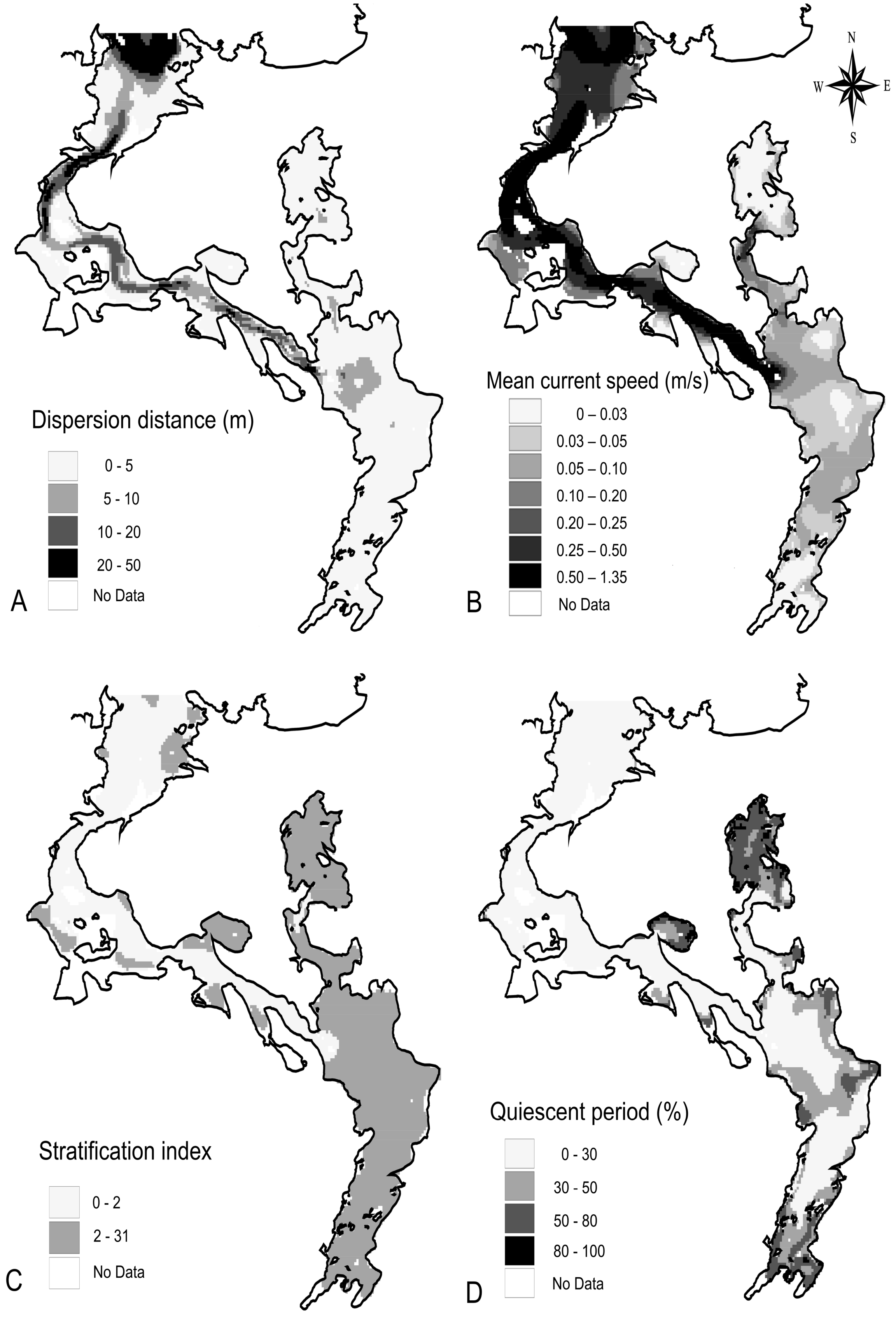

**Figure 5.5. Distributions of a) dispersion distance, b) mean current speed, c) stratification index, and d) quiescence period.**

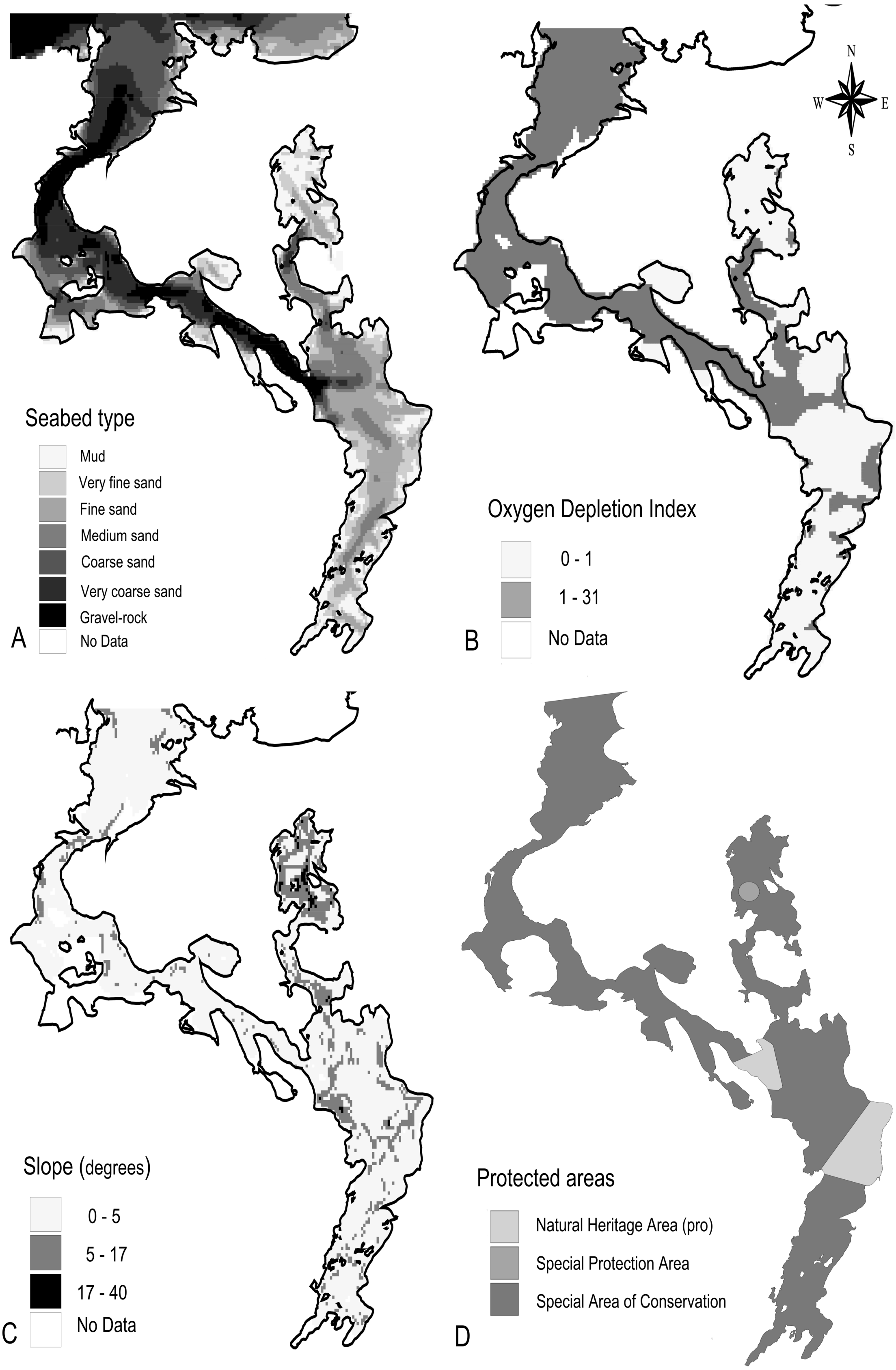

**Figure 5.6. Distributions of a) sea bed type, b) oxygen depletion index, c) slope and c) protected areas.**

### 5.5.2 Protected Areas.

Only a Special Protection Area at Greer Island in Kindrum and two Natural Heritage Areas in the third narrow and in the center of Broadwater (Fig 5.6d) were considered relevant and included in the GIS as Boolean constraints.

### 5.5.3 Oxygen depletion.

ODI maps (Figs 5.6b) show that the time required for the representative single salmon cage fish biomass to reduce the ambient concentration of oxygen to specified threshold level is only a problem in Kindrum, Millford and the central and northeast areas in Broadwater. For the rest of the Bay the current is strong enough to maintain the oxygen at an optimal level for salmon cage culture.

The oxygen measured in the proximity of the block cages (Fig 5.7) shows that there is a possibility that ambient concentration may be reduced to a low level due to the presence of the fish. The oxygen measurements were not taken during slack water at an unknown current velocity. For the two types of cage configurations considered (Fig 5.7) when the temperature was close to 16ºC the ambient dissolved oxygen concentration varied close to 7 mg/l.

For the first example, block cage 1, dissolved oxygen concentration was reduced from 7 mg/l to 5 mg/l and the cages were heavily fouled. The fish were also being fed at the time of measurement. The second example, block cage 2, also shows reduced dissolved oxygen concentration from 7 mg/l to 5 mg/l. The third example, block cage 3, was located in more hydrodynamically exposed conditions and showed only moderate dissolved oxygen depletion.

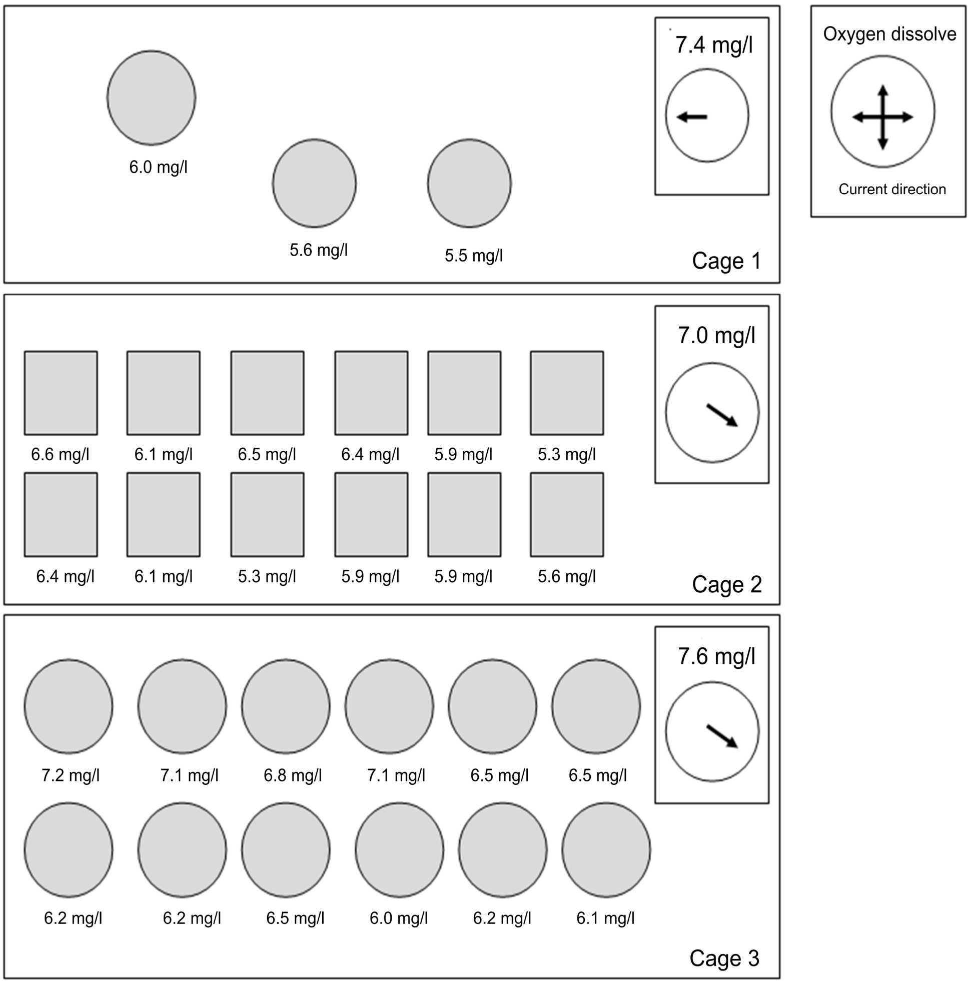

**Figure 5.7. Dissolved oxygen levels measured in the proximity of the block cages ( the circular and squares grey figures) illustrating the reduction in the ambient concentration of oxygen caused by fish biomass.**

Across all of the 16 sensitivity runs (Table 5.2) the various permutations and combinations of the learning and validation parameters showed that the change in rule weights, the validation method and number and types of fuzzy set appear to have significant influences in the sensitivity analysis (Fig 5.8). The values of accuracy and the number of unclassified cells varied in every model, showing that the models with weighted rules produced less unclassified cells (3.59%) while the trapezoidal models produced the highest (24.18%).

**Table 5.2 Summary characteristics of the sensitivity models.**

| Model * | No fuzzy sets | Accuracy % | Non classified % | Type fuzzy set | Rule weight | Validation |
|---|---|---|---|---|---|---|
| Model 1 | 3 | 83.33 | 1.58 | triangle | No | CV |
| Model 2 | 3 | 66.67 | 1.92 | trapezoidal | No | CV |
| Model 3 | 3 | 73.81 | 1.61 | bell | No | CV |
| Model 4 | 4 | 85.71 | 4.82 | triangle | No | CV |
| Model 8 | 4 | 78.57 | 23.01 | trapezoidal | No | CV |
| Model 12 | 4 | 85.71 | 0.19 | bell | No | CV |
| Model 5 | 4 | 76.19 | 13.34 | triangle | No | ST |
| Model 9 | 4 | 71.43 | 24.18 | trapezoidal | No | ST |
| Model 13 | 4 | 78.57 | 0 | bell | No | ST |
| Model 6 | 4 | 71.43 | 3.40 | triangle | Yes | C |
| Model 10 | 4 | 73.84 | 5.5 | trapezoidal | Yes | CV |
| Model 14 | 4 | 73.84 | 0.25 | bell | Yes | CV |
| Model 7 | 4 | 71.43 | 3.34 | triangle | Yes | ST |
| Model 11 | 4 | 73.81 | 3.59 | trapezoidal | Yes | ST |
| Model 15 | 4 | 73.84 | 0.49 | bell | Yes | ST |

*** All neuro-fuzzy models have following identical learning and validation parameters. Aggregation function, maximum; interpretation of classification results, winner takes all; No prior knowledge used; Size of the rule base, automatically determined; Rule learning procedure, best per class; Learning rate, 0.1: Stop controls maximum of epochs, 800; minimum number of epochs, 0; Number of epochs after optimum, 10: admissible classification errors, 0.**

The neuro-fuzzy classification of the training sites (42 in total) showed R values from 66.7 % to 85.7 % suggesting that they were well classified. The higher values were in the triangular and trapezoidal fuzzy data shapes. The accuracy of the final classifier selected was R= 85.71%, (36 correctly classified and 6 misclassified, with an estimated error value of ±16.5% from Cross Validation, N=10) and a Kappa coefficient of agreement of 81%. Unclassified cells in the whole spatial domain (of 1623 GIS cells) ranged from 0% to 24.18 %, the higher unclassified values being in trapezoidal fuzzy shapes models and the lowest in the bell fuzzy shapes models.

In order to provide a general description of the local hydrology and sea bed characteristics, depth, mean current velocity, quiescent period and granulometry were selected as classifiers in each vulnerability category (Table 5.3). These statistics show that the examples classified by the experts as most vulnerable tend to have longer periods of quiescent waters, the lowest mean current velocity, and the finest granulometry.

**Table 5.3. Descriptive statistic for the classifiers of the categories for environmental vulnerability.**

| | | Depth (m) | Mean Current velocity (m/s) | Quiescence (%) | Granulometry (mm) |
|---|---|---|---|---|---|
| Cat 1 | | | | | |
| | Mean | 13.70 | 0.35 | 2.36 | 1311.91 |
| | Sta Devs | 3.68 | 0.13 | 2.16 | 407.76 |
| | Min | 9.03 | 0.13 | 0.00 | 496.00 |
| | Max | 19.86 | 0.52 | 7.00 | 1854.00 |
| Cat 2 | | | | | |
| | Mean | 16.01 | 0.10 | 10.45 | 480.45 |
| | Sta Devs | 6.22 | 0.03 | 6.04 | 128.43 |
| | Min | 9.52 | 0.06 | 2.00 | 287.00 |
| | Max | 27.93 | 0.16 | 20.00 | 672.00 |
| Cat 3 | | | | | |
| | Mean | 19.32 | 0.04 | 32.18 | 368.73 |
| | Sta Devs | 7.20 | 0.02 | 10.38 | 71.00 |
| | Min | 11.70 | 0.02 | 16.00 | 250.00 |
| | Max | 31.83 | 0.07 | 48.00 | 466.00 |
| Cat 4 | | | | | |
| | Mean | 19.93 | 0.02 | 55.33 | 250.00 |
| | Sta Devs | 11.27 | 0.01 | 16.39 | 103.96 |
| | Min | 9.06 | 0.01 | 40.00 | 87.00 |
| | Max | 37.64 | 0.04 | 96.00 | 439.00 |

The 16 environmental vulnerability maps produced during the sensitivity runs showed that the majority of the models indicated similar locations of the vulnerability in the Narrows, Kindrum and Millford areas, although the total extent of the area for vulnerability categories 2 and 3 varied from model to model for Broadwater (Fig 5.8).

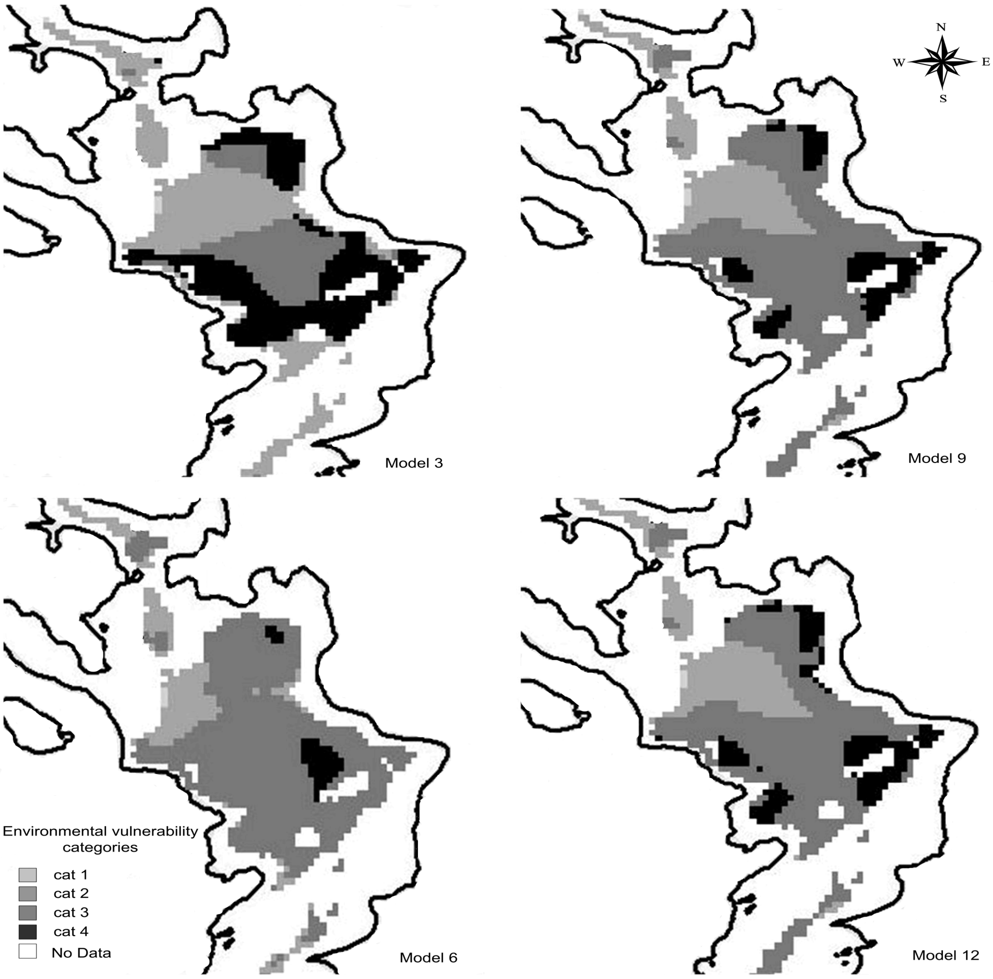

**Figure 5.8. Sensitivity analysis of environmental vulnerability in the study area developed from models 3, 9, 6 and 12.**

The Kindrum area had the highest level of unclassified cells. The environmental vulnerability tended to be lower where the hydrographic conditions were more dynamic (e.g. high mean current velocity, short periods of quiescent water and coarse sediment), and influenced stratification, oxygen depletion and distance of particulate waste dispersion. Four regions can be differentiated (Fig 5.9) with different levels of environmental vulnerability. The Outer Bay and the Narrows have low values of environmental vulnerability in categories 1 and 2. The northern part of Broadwater and areas in the proximity of Moross Channel have medium/low environmental vulnerability (Cat 2) but this increased from category 1 in the mouth of the Third

Narrows to category 4 in the Rosnakill area. The central part of the Broadwaters was characterised with medium/high (Cat 3) and high (Cat 4) values of vulnerability, whereas Kindrum and Milford showed the highest environmental vulnerability classification (Cat 4). The areas of vulnerability classes 1 to 4 were, respectively, approximately 6 %, 17 %, 44 %, and 33% of the total area from the final model.

The mean percentage of total sediment nitrogen concentration (an indicator of likely environmental impact by fish farms) in each vulnerability class are summarised in the table insert in Fig 5.10. In the final model selected the nitrogen concentration declines from the highest vulnerability classes to the lowest indicating that the areas classified as most vulnerable tended to have higher nitrogen concentrations (Fig 5.10). The percentage of seabed total nitrogen was significantly different between the vulnerability categories (Kruskal-Wallis; $\chi^2$= 29.012, df 3, p<0.001). The results of the pairwise Mann-Whitney U tests also indicated a significant difference in nitrogen levels for each pair of environmental vulnerability categories. Spearman's correlation coefficient, (Spearman's rho = 0.862, p< 0.001), showed a strong correlation between increasing percentages in sediment nitrogen and increasing vulnerability from Categories 1 to 4, (Fig 5.10), indicating a clear relationship between the modeled environmental vulnerability and the influence by fish farms on seabed.

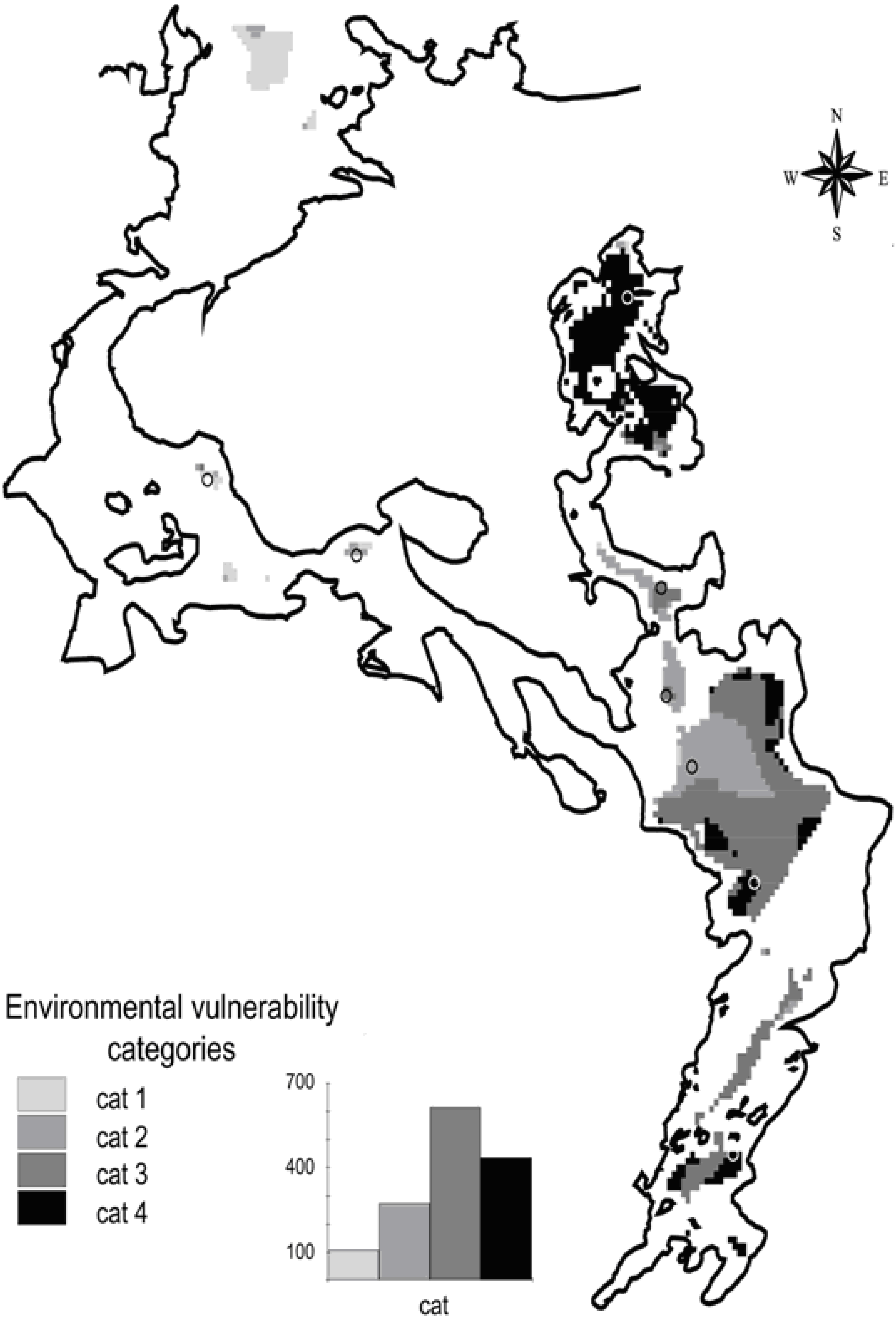

**Figure 5.9. Environmental vulnerability classes in the study area. The histogram shows the numbers of cell per category.**

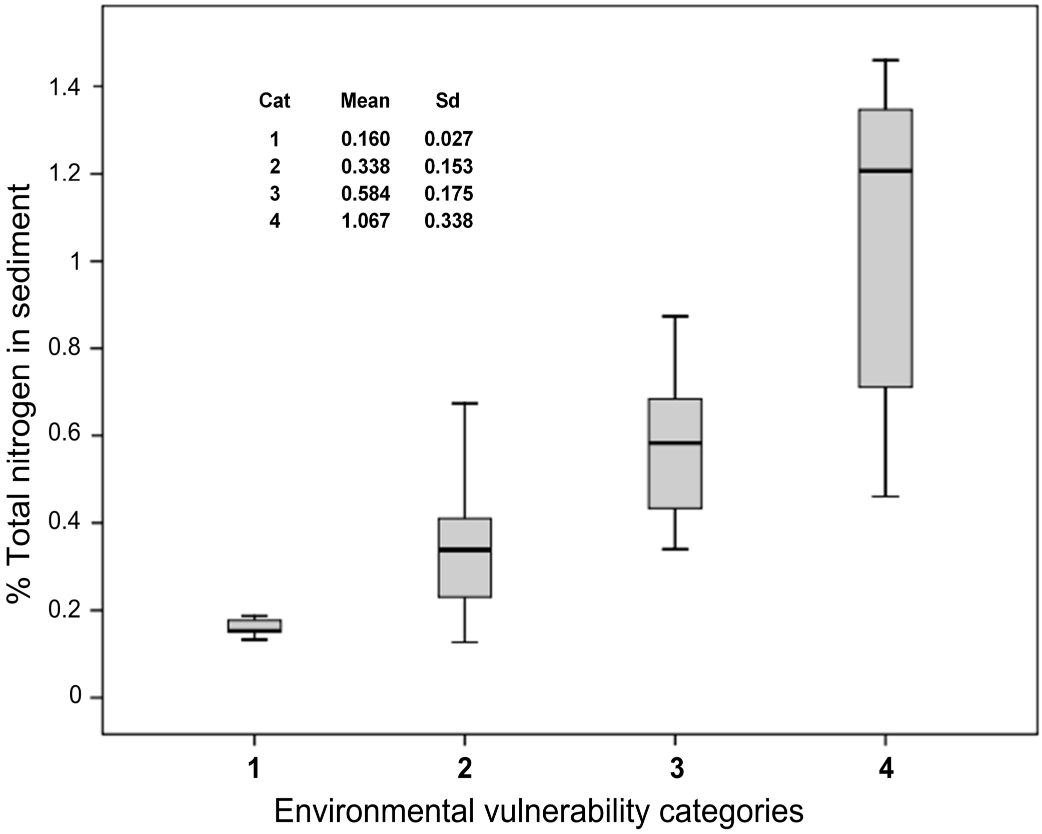

**Figure 5.10. The relationship between vulnerability classes and percent of total nitrogen in sediment.**

## 5.6 Discussion.

The spatial information needs for decision-makers for aquaculture planning can be well served by geographical information systems (Kapetsky and Travaglia, 1995). However, only two applications of using GIS for site selection for coastal salmon aquaculture at a similar scale as in this study can be found (Ross et al., 1993; Krieger and Mulsow, 1990). Nath et al. (2000) also noted that the deployment of spatial decision support in aquaculture planning and management continued to be very slow. This is attributable to a number of constraints including a lack of appreciation of the technology, limited understanding of GIS principles and associated methodology, and inadequate organizational commitment to ensure continuity of these spatial decision support tools.

The Scottish Environment Agency SEPA, (SEPA, 2005) suggest that local hydrography is fundamental in any decision making process. Hydrodynamic characteristics such as tidal flow, water exchange, residual circulation, patterns of turbulence, wind and wave energy, and flocculation of particles (aggregation) will determine near and large-scale patterns of particle dispersion and discharges from the cages (Hargrave, 2003 ; Wildish et al., 2004) and play the main role in the characterization of the environmental vulnerability. In an aquaculture context, strongly stratified marine systems can be an important factor in the dispersal of organic matter (Wildish et al., 2004). The Hunter-Simpson criteria provides a general view of the water column stability due to tidal mixing, and as the area has no influence from river discharge this is not taken into account the wind and seabed mixing are not taken into account. The main reason for selecting this criterion was the simplicity and ease of calculation from the 3D hydrodynamic modeled data set, although only the worst case scenario of thermal stratification was modeled for the area.

Aquaculture has many potential environmental effects and impacts, including an accumulation of solid nutrient waste and associated oxygen degradation effects under the site, respiration of fish within a confined area leading to lowered oxygen levels under certain hydrological conditions, and the release of excess nutrients into the water column possibly causing higher pelagic productivity (Silvert, 1992).

Hargrave et al. (1995) noticed that ecological benthic variables were correlated with levels of organic matter sedimentation. The author suggest that the biological processes are not always sufficient to limit organic matter accumulation especially in areas where hydrographic conditions and/or low current velocity result in low rates of oxygen supply to the sediment surface. Carroll et al. (2003) classified the potential sensitivity to impacts from fish farming based on the average current velocity at a site. Two main hydrographic characteristics which provide environmental vulnerability and carrying capacity of the area, the mean current velocity, and the period of quiescent water, were incorporated into this study.

Fish farms in areas of weak currents have the potential to reduce the concentration of dissolved oxygen below ambient values on localized scales, varying temporally and spatially. This depletion was calculated using the Oxygen Depletion Index (Page et al., 2005) which was chosen because of its relative ease of calculation in the whole spatial domain using the current velocity from the modeled data set. ODI however, is still only a preliminary indicator of the potential influence of the fish farming component on the concentration of dissolved oxygen.

Organic deposition is usually restricted to the immediate area of the cages and most studies have shown that the local extent of altered benthic community structure and biomass is limited to less than 50 m, (Holmer et al., 2005). The GIS cell dimension selected for this study (50 x 50 meters) takes this into account. The maximum pellet dispersion distance provides a simple waste dispersion capacity of a location. In this study, only pellet dispersion was used because if the faecal dispersion distance modeled is more than the grid resolution, 50 meters, the faecal dispersion will be affected by other value of current velocity of a continuous cell, the pellet dispersion distance was always less than the grid resolution for this reason was only selected. The MOM model used a more sophisticated dispersion capacity of a location based upon the dispersion length, (Stigebrandt et al., 2004). Simple dispersion measurements were selected as they are easy to use and easier for the experts involved in the classification of the training sites to understand.

Water depth and current velocity are critical factors determining patterns of sedimentation around cage sites. Cages change the bottom type to more fine-grained sediments through enhanced deposition of flocculated, fine-grained material. Viaroli et al. (2004) propose adoption of the simple and rapid assessment of the potential vulnerability of sediment for the identification of vulnerable sites, where the finer the granulometry the more vulnerable the site.

Hargrave (2002) used a decision support system (DSS) to assess far- and near-field variables potentially affected by marine finfish aquaculture found that intermediate conditions where boundaries between acceptable and unacceptable effects are not clearly known or agreed upon could be assessed by a fuzzy classification technique. Because of this, there is concern about how to use vague environmental boundary conditions without compromising scientific objectivity. Silvert (1997) suggested that fuzzy logic is ideally suited to the processing of this kind of data. Salmon aquaculture has many potential environmental effects, and it is clear from the present study of marine environmental vulnerability that susceptibility and vulnerability are fuzzy concepts.

Assessment of environmental vulnerability in the present study used simple descriptive factors (high, low, medium). However, geographical and classification boundaries are difficult to define, and boundaries are not sharply defined and the employment of prior scientific knowledge is required. Fuzzy sets naturally lend themselves to modelling this uncertainty in vague and ambiguous conditions and coincide with the views of Jacquez et al., (2000) on continuousness and ambiguity. The advantage of fuzzy classifiers is that implicit knowledge acquired from experts in coastal aquaculture activities can be incorporated into the fuzzy neural network, and that data driven knowledge can be learned from training samples to enhance the accuracy of the output. While the objective of the training samples is to identify a set of cells that accurately represents the variation present within each class, clearly the analyst must know the correct class for the selected cells. Campbell (2002) proposed that the analyst must have some field experience with the specific area and should be familiar with the particular problem the study is to address at the point at which the expert and scientific knowledge is taken into consideration. In the present study, expert (supervised) classification was used to develop a neuro-fuzzy classifier from which the remaining areas could be classified without the limitations of strict boundaries among environmental vulnerability classes. This capacity is the strength of this innovative approach and could open a new route for spatial management under conditions of uncertainty and data scarcity.

Dixon (2005) noted that all studies using neuro-fuzzy techniques should conduct a sensitivity test to determine which model strategy is more suitable for the region and the environmental problem. The results of the present study agree with those of Dixon, who found that changes in the shape of the fuzzy sets, the nature of the rule weights, and the validation techniques used during the learning processes could all lead to different class assessment. Although correct selection and parameterization is important, the final classifiers selected produced a highly accurate outcome.

Of the few studies which have examined nitrogen flow through intensive cage farms in marine waters, most have concluded that the majority (67-80 %) is lost to the environment either as dissolved excretory products or by benthic flux of solid wastes from the cages (Hall et al.,1992;Holmer et al., 2005). The salmon biomass licence varies among cage sites. The higher tonnage sites, Glinks (cat 1) and Millstone (cat 2) are situated in the narrows, where the classification showed the lowest values of environmental vulnerability and total nitrogen in sediment. The highest values of vulnerability and nitrogen in sediment are in the areas with the lowest biomass licence, Kindrum and Milford areas both with cat 4. This suggests that the percentage of total nitrogen used as an environmental indicator is not influenced by the salmon biomass. Sediment nitrogen is often used as a more accurate indicator of sediment enrichment, due to the fact that this is mostly derived from external inputs, such as cage wastes. Perhaps a more reliable indicator of nutrient inputs to sediment is a measure of organic nitrogen content. Nitrogen levels reflect the nutrient status of sediments and unlike carbon, are not influenced by the presence of shell matter (Telfer and Robinson, 2003).

The neuro fuzzy models perform reasonably well at differentiating between areas with different nitrogen concentrations in sediment providing a final classification in which the highest mean nitrogen value is in Class 4. The non parametric Kruskal-Wallis test and the Spearman rank correlation showed that the differences between environmental vulnerability classes is significant and with a high trend of increasing values nitrogen values through the classes.

The environmental vulnerability will be defined on the basis of the intrinsic properties and the nature of the aquaculture activity. Once identified, different vulnerable areas can then be subjected to use restrictions, codes of practice or targeted for more detailed assessment. Outputs produced as GIS layers can then be assessed against relevant criteria to determine marine environmental vulnerability and may also be linked to appropriate planning responses or easily incorporated in an aquaculture Spatial Decision Support System (SDSS). The neuro fuzzy technique can appropriately classify coastal areas into different levels of environmental vulnerability to a range of aquaculture activities. It is, therefore, a useful tool in identifying locations where such activities have a higher risk of contaminating the marine environment. This study used an adaptive neuro-fuzzy system to train, adapt and classify areas of vulnerability to aquaculture in a complex coastal scene and it is suggested that this approach may have advantages over previously used methods.

## 5.7 Acknowledgments.

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# Chapter 6 Separability indexes and accuracy of Neuro-fuzzy classification in Geographical Information Systems for assessment of coastal environmental vulnerability.

**Authors: J. Moreno [1] T. Telfer and L.G. Ross.**

This chapter describes the development of a Neuro-fuzzy classifier for supervised and hard classification of GIS cells in the coastal environmental vulnerability using minimal training sets and further evaluation and analysis of the quality of the classification achieved. The training numerical values of the GIS cells classified have been extracted from the GIS layers developed in chapter 5. A second training data set used was the multivariate Iris Flowers data set a classic data set used in statistical studies.

The main author, J Moreno Navas, conducted all field work and developed all sub-models and final models. Prof Lindsay G Ross and Dr Trevor C Telfer provided supervisory and editorial support throughout the whole study.

The body of the text is presented as a publication-ready manuscript. This manuscript has been submitted to Applied Soft Computing: an international journal promoting an integrated view of soft computing to solve real life problems.

# Separability indexes and accuracy of Neuro-fuzzy classification in Geographical Information Systems for assessment of coastal environmental vulnerability.

**Authors: J. Moreno [1] T. Telfer and L.G. Ross.**

**6.1 Abstract.** The aim of this study was the development, evaluation and analysis of a Neuro-fuzzy classifier for a supervised and hard classification of coastal environmental vulnerability due to marine aquaculture using minimal training sets within a Geographic Information System (GIS). The neuro-fuzzy classification model NEFCLASS–J, was used to develop learning algorithms to create the structure (rule base) and the parameters (fuzzy sets) of a fuzzy classifier from a set of labeled data.

The training sites were manually classified based on four categories of coastal environmental vulnerability through meetings and interviews with experts having field experience and specific knowledge of the environmental problems investigated. The inter-class separability estimations were performed on the training data set to assess the difficulty of the class separation problem under investigation. The two training data sets did not follow the assumptions of multivariate normality. For this reason Bhattacharyy and Jeffries-Matusita distances were used to estimate the probability of correct classification.

Further evaluation and analysis of the quality of the classification achieved a high value for the Kappa coefficient of agreement and a good overall accuracy. For each of the four classes the user and producer values for accuracy were between 77 % to 100%.

In conclusion, the use of a neuro-fuzzy classifier for a supervised and hard classification of coastal environmental vulnerability has demonstrated an ability to derive an accurate and reliable classification using a minimal number of training sets.

Keywords: Neuro-fuzzy classification, Geographic Information System, separability indices, coastal environmental vulnerability.

[1] Corresponding author: Institute of Aquaculture. University of Stirling. FK94LA. Stirling.UK (jmn1@stir.ac.uk) Tlf :01786767882 .Fax: 01786472133

## 6.2 Introduction.

Geographic Information Systems (GIS) provide an easy-to-use graphical user interface for visualization and interrogation of results, and as an input for data for the development of spatial environmental models. The integrative approach and analytical capabilities of GIS are a powerful tool to effectively guide environmental management of marine aquaculture. The basics of classification within Geographical Information Systems is the process of assigning cells, the unit of information in raster data, to classes. GIS and remote sensing software places almost no constraints upon a user's selection of classification methods and the user can to choose appropriate procedures and settings that are fit for purpose. Campbell (2002) and Smith et al. (2007) described selected examples and definition of classifiers for such classification systems. The latter authors define hard classification as where the objects to be classified are regarded as discrete and distinct items that can only reside in a single class. Conversely, soft or fuzzy classification exists where objects have an uncertain class membership and /or unclear boundaries. Within a GIS framework the objective of classification is to identify distinct areas or features (represented as a collection of cells in space) and assign all occurrences of such features to distinct groupings. This is either performed semi-automatically (supervised but requiring training data) or automatically (unsupervised by statistics methods). Supervised classification procedures require considerable interactions with the user, who must guide the classification by identifying areas and/or training sites, that are known to belong to each category. Unsupervised classification takes place with only minimal interaction with the user. A third category of classification uses hybrid classifiers which share characteristics of both methods (Campbell, 2002).

Real data can be used to train a neuro-fuzzy system to identify a group of spatial cells within the GIS that accurately represents the variation present within each class. Here the class is designated by the analyst who must know the correct class for the selected cells (Campbell, 2002), meaning that the analyst must have considerable field experience in the area of investigation and be familiar with the particular problem being addressed. Many authors comment that the quality and size of training data are of key importance. Kavzoglu (2009) highlighted the fact that the data set developed to train the system by the analyst makes a considerable impact on the performance of a supervised classification process. The training data must therefore be defined in such a way that they are typical and representative of each individual class.

A Separability Index can be used to estimate the degree of closeness of classes within the training data before the classification system is selected, and estimation of separability can be performed to assess the difficulties of the class separation issues and this has been extensively used by researches in remote sensing (Kavzuglu and Mather, 2001).

Another important step in classification using training data is to evaluate the robustness and strength of the classes defined by ground-truthing or comparing them with field data (Smith et al., 2007). If the training data gives classifications containing a large number of unclassified or misclassified samples, it can be considered as unrepresentative and should be either supplemented or replaced.

Static models within GIS represent single points in time and typically combine multiple inputs into a single output (Longley et al., 2005), but the results are often of great value as predictors or indicators. Spatial models that combine a variety of parameters as inputs to procedures which generate final mapped output are widely used, particularly in environmental modeling. Ambiguity also arises in the conception and construction of indicators and in classification scenes. Longley et al. (2005) suggest that the classes used for maps are often fuzzy in such a way that two people asked to classify the same location might disagree, either because the classes themselves are not perfectly defined, or because opinions vary. There are “soft computing” methods which take these demands into consideration.

The term “soft computing” was coined by Zadeh (1965), the founder of fuzzy logic. Soft computing includes approaches to human reasoning that try to make use of the human tolerance for incompleteness, uncertainty, imprecision and fuzziness in decision making processes (Nauck et al., 1997; Nauck et al., 1999). Fuzzy logic provides yet another framework for re-doing, re-thinking and re-expressing most conventional modelling and statistical applications used in spatial applications (Openshaw and Openshaw, 1997). Threre are few classifiers derived from computational intelligence used in GIS such as, multi-level perceptron, self organizing maps , and fuzzy artmaps (Smith et al., 2007). Some of the most well-known neuro fuzzy pattern recognition and classification systems include FuNe, (Halgamuge and Glesner, 1994), Fuzzy RuleNet, (Tschichold-Gürman, 1994) ANFIS, (Jang, 1993) Fuzzy Artmap, (Carpenter et al., 1992).

Fuzzy data sets provide a formal approach for incorporating ambiguity and lack of quantitative data in a classification scheme. Many types of ecological and environmental data are qualitative or use discrete categories and boundaries and for these reasons are difficult to incorporate into classification schemes designed to produce a numerical index of ecological quality (Silvert, 1997). Openshaw and Openshaw (1997) identified several instances in the use of GIS where adopting a fuzzy approach may be necessary or beneficial, for example when there is little or no training data as may be the case with aquaculture environmental problems even though there is sufficient expert knowledge to specify a spatial model that may be used to make environmental predictions and classification. Hargrave (2002) used a decision support system (DSS) to assess far- and near-field variables potentially affected by marine finfish aquaculture and found that intermediate conditions where boundaries between acceptable and unacceptable environmental effects are not clearly known or agreed upon could be assessed by a fuzzy classification technique.

Within such classifications it is usual to consider knowledge bases and management decisions that exist within a general management framework. As management decisions are influenced directly by the quality and quantity of information available in relevant knowledge bases, knowledge and decision making are intrinsically connected (Close and Hall, 2006). Fuzzy sets provide a consistent method for incorporating ambiguous or qualitative data into a classification scheme. The neuro-fuzzy classifier has several advantages as vague knowledge can be used when boundaries are difficult to define. The classifier is interpretable in its original form and is easy to implement, use and understand (Nauck and Kruse, 1999).

The aim of this study was the development of Neuro-fuzzy classifiers for a supervised and hard classification of coastal environmental vulnerability due to salmon marine cage aquaculture. The study undertook extended evaluation and analysis of the quality of the classification achieved. The inter-class separability estimation, using several separability indices, were performed on a training data set to assess the difficulty of class separation.

## 6.3 Neuro fuzzy classification and project design.

The neuro-fuzzy software NEFCLASS- J (NEruro Fuzzy CLASSifier) for JAVA platforms was used. NEFCLASS–J, offers learning algorithms to create the structure (rule base) and the parameters (fuzzy sets) of a fuzzy classifier from a set of labeled data, the aim of the approach being to create interpretable classifiers. The software applies a fuzzy variant of the well-known back propagation algorithm to tune the characteristic parameters of the fuzzy membership functions.

The software architecture and functions, described in Nauck and Kruse (1999), has a three-layer fuzzy perceptron (Fig 6.1), the first layer, $\chi_n$, consisting of input neurons, the second layer, Rn, of hidden neurons and the third layer, Cn, of output neurons. The difference between this and a classical multilayer perceptron is that the weights now represent fuzzy sets and that the activation functions are now fuzzy set operators. The hidden layer neurons represent the fuzzy rules and the output layer neurons the different classes of the classification problem with one output neuron per class.

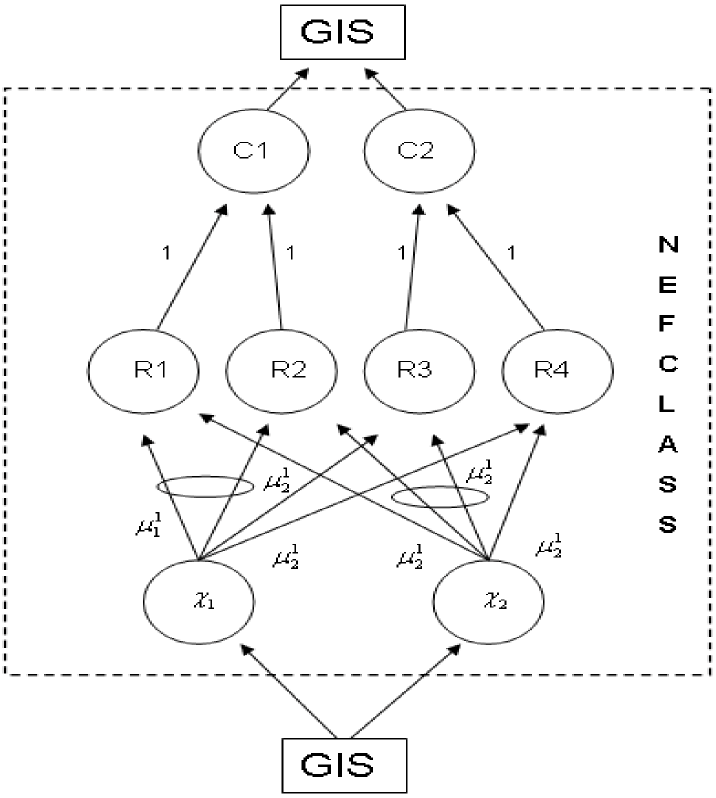

**Figure 6.1. An idealized data flow of the project and the NEFCLASS architecture.**

The latter authors suggest that after an observation has been propagated through the network, its predicted class is assigned according to the output neuron with the highest activation value (winner-takes-all). The fuzzy sets are defined by membership functions and rule bases. Shapes of the fuzzy sets are defined by the membership functions, these being a representation of a linguistic variable to a fuzzy set as a matter of degree (Fig 6.2). NEFCLASS-J allows users to select types of fuzzy sets and strategies for the rule base generation during the learning processes.

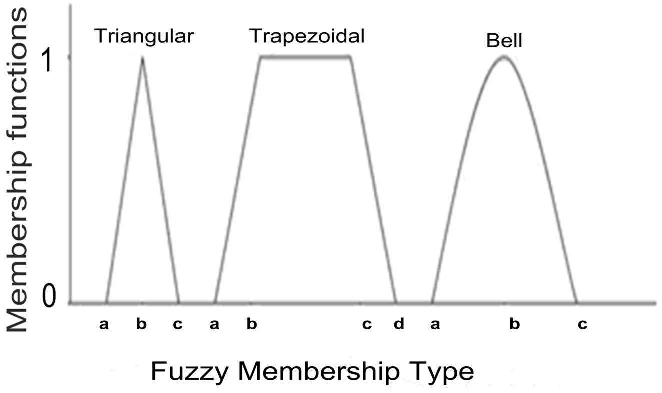

**Figure 6.2. Examples of different membership functions, triangular, trapezoidal, bell shape, were defined by four parameters a, b, c, and d respectively, modified from Nauck et al. (1997)**

There are three kinds of functions that are commonly used; triangular, trapezoidal and bell-shaped functions. Examples of different membership functions, trapezoidal, triangular and bell shape were defined by four parameters a, b, c, and d respectively, as shown in equations 1 to 3.

$$(x:a,b,c,d) = \begin{cases} 0 & x<a \\ (x-a)/(b-a) & a\leq x<b \\ 1 & b \leq x <c \\ (d-x)/(d-c) & c \leq x <d \\ 0 & x \geq d \end{cases} \qquad \text{(Trapezoidal, equation 1)}$$

$$(x:a,b,c) = \begin{cases} 0 \quad x<a \\ (x-a)/(b-a) \quad \text{if } x \in [a,b] \\ (c-x)/(c-b)\,) \quad \text{if } x \in [b,c] \\ 0 \quad x>c \end{cases} \qquad \text{(Triangular, equation 2)}$$

**(x:a,b,c) =** $$\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}}$$ **(Bell, equation 3)**

NEFCLASS-J allows users to select the type and initial number of fuzzy sets, as well as specifying the maximum number of rule nodes that may be created in the hidden layers and strategies for the rule based generation during the learning processes. The learning process can be visualized in Fig 6.3. and was explained by Nauck et al. (1997), who noted that the  purpose of the learning algorithm is to create a rule base first and then to refine it by modifying the initially given membership functions. The rule base will be created by finding, for each pattern in the training set, a rule that best classifies it. After all patterns are processed once the rule base is completed. The learning algorithm of the membership functions uses the output error, which indicates whether the degree of rule fulfillment should be higher or lower, to shift the membership function of the fuzzy sets used and to increase or decrease their support. In a third step, using NEFCLASS-J the rule base may be reduced, if required, by removing rules and variables based on a simple algorithm using several heuristics methods.

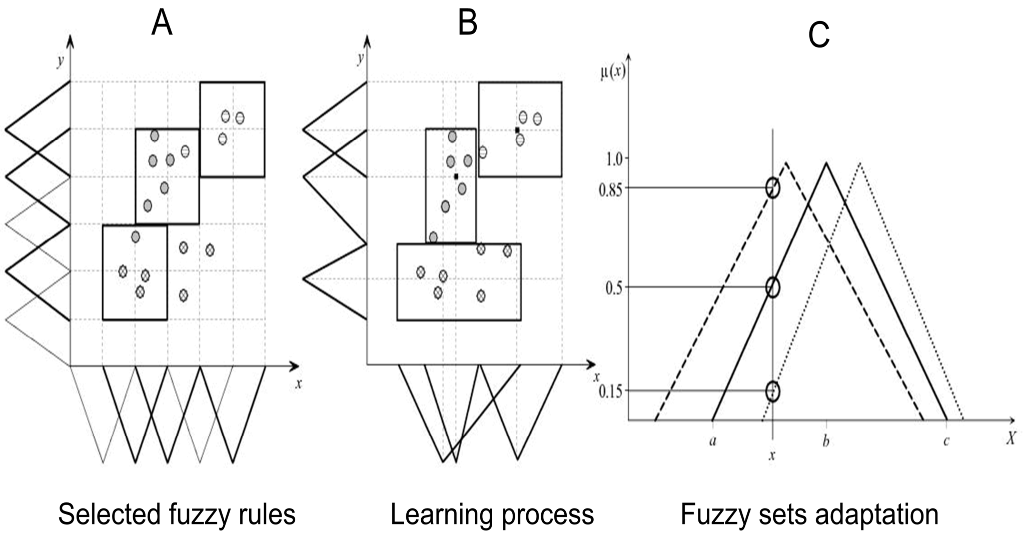

**Figure 6.3 The learning process: the rules are selected from a grid structure in feature space that is given by the fuzzy sets of the individual variables (A), the membership functions changes after the learning algorithm process (B) , and the adaption process of the membership function parameters, (C) modified from Nauck et al. (1997).**

## 6.4 Methods.

Two data series were selected as classifier training samples for use in this study. The environmental vulnerability categories were manually classified training sites with mostly different hydrodynamic characteristics selected using stratified random sampling in different geographical areas of the study area using the GIS. The training samples were exported as *.txt files and the data were manually inspected and classified.

From the GIS raster data layers a total of 42 training sites were sampled in four categories based on expert opinions from focus group meetings and interviews. A total of 6 experts, with more than 15 years research and academic experience in environmental management of salmonid culture and 2 years aquaculture industry experience, were used. The parameters used included mean current speed, quiescence time of water currents, stratification index, sediment granulometry, estimated maximum distance of deposition of solid fish cages wastes and the Oxygen Depletion Index, (Page et al., 2005). Descriptive statistics are shown in Table 6.1 and linear correlations among parameters are shown in Table 6.2. The second training data set used was the multivariate Iris Flowers data set of Fisher (1936), a classic data set used in statistical studies.

The performance of the classifiers was evaluated using recognition rate $R$ (Abe 2001) given by:

$$R = \frac{100M_c}{M}(\%) \quad \text{(Equation 4)}$$

where Mc is the number of correctly classified data and M is the number of classified data. A 10-fold cross validation was used.

The accuracy of the classifiers in defining classification was assessed using Kappa analysis (Congalton and Mead, 1983), a discrete multivariate analysis technique. The Kappa Coefficient of Agreement is given by:

$$\hat{K} = \frac{N\sum_{i=1}^{K} x_{ii} - \sum_{i=1}^{k}(x_i \times x_{+1})}{N^2 - \sum_{i=1}^{k}(x_i \times x_{+i})} \qquad \text{(Equation 5)}$$

where K is the number of rows (classes) in a matrix, $X_{ii}$ is the number of observations in row ‘i’ and column ‘i’, and $X_{+i}$ are the marginal totals for row ‘i’ and column ‘i’, respectively, and N is the total number of observation. Landis and Koch (1977) suggest that a value of K = 0.8 (80%) represents a strong agreement or accuracy, K = 0.4 to 0.8 represents moderate agreement, and K < 0.4 represents poor agreement.

The inter class separability indices, described by Kavzoglu and Mather (2002); Divergence (D), transformed Divergence (TD), the Bhattacharyya distance ($B_y$) and the Jeffries-Matusita distance ($JM_y$) were also calculated. Given two feature classes ( *i* and *j*) the separability indices were calculated according to the following formulae:

$$D_{ij} = \frac{1}{2} tr\left[\left(V_i - V_j\right)\left(V_j^{-1} - V_i^{-1}\right)\right] + \frac{1}{2} tr\left[\left(V_i^{-1} + V_j^{-1}\right)\left(M_i - M_j\right)\left(M_i - M_j\right)^T\right] \quad \text{(Equation 6)}$$

$$TD_{ij} = c\left\{1 - \mathbf{exp}\left(-D_{ij}/8\right)\right\} \quad \text{(Equation 7)}$$

$$B_{ij} = \frac{1}{8}\left(M_i - M_j\right)^T \left[\frac{\left(V_i + V_j\right)}{2}\right]^{-1} \left(M_i - M_j\right) + \frac{1}{2}\mathbf{ln}\frac{\left|\left(V_i + V_j\right)/2\right|}{\sqrt{\left|V_i\right|\left|V_j\right|}} \quad \text{(Equation 8)}$$

$$JM_{ij} = \sqrt{2\left(1 - e^{-B_{ij}}\right)} \quad \text{(Equation 9)}$$

where the tr[ ] indicates the trace of a matrix (the sum of its diagonal elements), $V_i$ and $V_j$ are the variance–covariance matrices for class i and j, and $M_i$ and $M_j$ are the corresponding sample mean vectors and c is a constant that define the range of transformed divergence values is chosen as 2000 following Jensen (1996).The separability index was calculated using a Mat Lab M-file (Dr T Kavzoglu *pers comm.*). The training data sets were analyzed using a Henze-Zirkler test (Henze and Zirkler, 1990) to assess the multivariate normality. The test was calculated using a Mat Lab M-file (source: http://www.mathworks.co.jp/matlabcentral/fileexchange/authors/7089).

## 6.5 Results.

Descriptive statistics for variables of the data set of environmental vulnerability are displayed in Table 6.1. Table 6.2 shows a high level of correlation between variables except for Variable 1 (depth). The correlation is not significant at the level 0.01 between variable combinations of 1&4 ( R= -0.300; *p*=0.054) and 1&7 ( R= -0.13; *p*=0.422).

**Table 6.1. Descriptive statistics of variables for the data set of environmental vulnerability.**

| Variable | mean | std. deviation | minimum | maximum |
|---|---|---|---|---|
| 1 Depth (m) | 17.11 | 7.44 | 9.03 | 37.64 |
| 2 Mean velocity (m/s) | 0.13 | 0.15 | 0.01 | 0.52 |
| 3 Quiescent (%) | 23.64 | 22.02 | 0.00 | 96.00 |
| 4 Bottom type (mm) | 619.57 | 472.37 | 87.00 | 1854.00 |
| 5 Stratification | 3.97 | 1.46 | 1.39 | 6.46 |
| 6 ODI | 4.36 | 4.84 | 0.45 | 16.86 |
| 7 Dispersion (m) | 8.43 | 7.81 | 0.71 | 36.55 |

**Table 6.2. Pearson correlation table among environmental vulnerability variables.**

| Var | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 \| | | -0.39 | 0.39 | -0.30 | 0.58 | -0.40 | -0.13 |
| 2 \| | | | -0.66 | 0.95 | -0.91 | 1.00 | 0.91 |
| 3 \| | | | | -0.66 | 0.84 | -0.66 | -0.60 |
| 4 \| | | | | | -0.86 | 0.95 | 0.90 |
| 5 \| | | | | | | -0.91 | -0.77 |
| 6 \| | | | | | | | 0.90 |

**The correlation is not significant at the level 0.01 between variables combination of 1-4 and 1-7.**

The training data sets did not follow the assumptions of multivariate normality as the Henze-Zirkler test was not significant for both data sets. For the environmental vulnerability data sets $T$ = 1.6305, $p$ <0 .001 and for the iris data set, $T$ = 2.3332, $p$ <0 .001. Therefore it was impossible to assess the degree of discrimination between classes present in the data set through multivariate statistical tests (see Kavzoglu and Mather, 2002). The inter-class separability indices are summarized in Tables 3 and 4. Considering environmental vulnerability (Table 6.3) the lowest divergence values were for the combination of variables; 3&4, 1&2 and 2&3 in Bhattacharyya and Jeffries-Matusita indexes, while the highest value was for the combination of variables 1&4. The index for transversal divergence showed a constant value of 2000 for all variable combinations. The separability indexes for the iris dataset (Table 6.4) showed the lowest values for the combination of variables 2&3.

**Table 6.3. Separability indexes among environmental vulnerability classes**

| Classes | Divergence | Tran. Div. | Bhattacharyya | Jeffries-Matusita |
|---|---|---|---|---|
| 1-2 | 272.029 | 2000 | 3.380 | 1389.939 |
| 1-3 | 5079.020 | 2000 | 4.856 | 1408.698 |
| 1-4 | 12543.546 | 2000 | 7.123 | 1413.643 |
| 2-3 | 983.485 | 2000 | 3.104 | 1382.125 |
| 2-4 | 1062.440 | 2000 | 6.756 | 1413.390 |
| 3-4 | 181.633 | 2000 | 3.949 | 1400.522 |
| **Average** | 3353.692 | 2000 | 4.861 | 1401.386 |

**Table 6.4. Separability indexes among classes in the iris data set.**

| Classes | Divergence | Tran. Div. | Bhattacharyya | Jeffries-Matusita |
|---|---|---|---|---|
| 1-2 | 221.068 | 2000.000 | 13.341 | 1414.212 |
| 1-3 | 454.305 | 2000.000 | 25.056 | 1414.214 |
| 2-3 | 17.923 | 1787.157 | 1.964 | 1311.296 |
| **Average** | 231.099 | 1929.052 | 13.454 | 1379.907 |

A classification was performed using the training data set. Statistical analysis through a confusions matrix (Table 6.5) for the test data included 42 examples in total and 11 cases for the classes 1,2,3 and 9 for class 4. The overall accuracy, given in Table 5, was R=85.71%, (where 36 classes were correctly classified and 6 misclassified, and estimated error value of ±16% from a 10-fold cross validation ) with Kappa coefficient of agreement of K = 81%. It was also noticed that a considerable number of cases were misclassified in class 2 and class 3, 3 and 2 respectively (Table 6.5). As can be seen in Table 6.6, each class showed accuracy values between 77 % and 100%. Users' accuracy ranged between 77% and 100%, while the producers' accuracy ranged between 79% and 100%. The lowest value, 77%, was in class 4 classified by the users.

**Table 6.5. Confusion matrix environmental vulnerability.**

Predicted Class

| | 1 | 2 | 3 | 4 | sum |
|---|---|---|---|---|---|
| 1 | 9 | 2 | 0 | 0 | 11 |
| 2 | 0 | 11 | 0 | 0 | 11 |
| 3 | 0 | 1 | 9 | 1 | 11 |
| 4 | 0 | 0 | 2 | 7 | 9 |
| sum | 9 | 14 | 11 | 8 | 42 |

**Correct: 36 (85.71%), Misclassified: 6 (14.29%). Kappa Index of Agrement: 81 %**
**Aggregation function, maximum; Number of fuzzy sets, 4; interpretation of classification results, winner takes all; No prior knowledge used; Size of the rule base, automatically determined; Rule learning procedure, best per class; Learning rate, 0.1: Stop controls maximum of epochs, 800; minimum number of epochs, 0; Number of epochs after optimum, 10: admissible classification errors 0.**

**Table 6.6. Classification accuracies for classes.**

| Training data | class accuracy | | | | overall accuracy (%) |
|---|---|---|---|---|---|
| Users' accuracy | 1 | 2 | 3 | 4 | |
| | 82% | 100% | 82% | 77% | 85.71% |
| Producers' accuracy | 1 | 2 | 3 | 4 | |
| | 100% | 79% | 81% | 87% | |

In the confusion matrix (Table 6.7) for the iris data set, which included 150 examples consisting of 50 cases in 3 classes, the overall accuracy was R=96% (where 144 examples were correctly classified and 6 misclassified). The Kappa coefficient of agreement for this data was K = 94 %. The confusion matrix for both data sets showed that the misclassified training examples were for the combination of variables with lowest separability index values.

**Table 6.7. Confusion matrix iris data set.**

Predicted Class

```
   |     1      2        3         sum
----------------------------------------
  1 |     50     0        0          50
  2 |      0    48        2          50
  3 |      0     4       46          50
-----------------------------------------
  sum     50     52      48        150
```

**Correct: 144 (R = 96%), Misclassified: 6 (4 %). Kappa Index of Agreement: K = 94 %**

**Aggregation function, maximum; Number of fuzzy sets, 4; interpretation of classification results, winner takes all; No prior knowledge used; Size of the rule base, automatically determined; Rule learning procedure, best per class; Learning rate, 0.1: Stop controls maximum of epochs, 800; minimum number of epochs, 0; Number of epochs after optimum, 10: admissible classification errors 0.**

## 6.6 Discussion.

Openshaw and Openshaw (1997) identified several types of GIS problem where adopting a fuzzy approach may be necessary or beneficial, for example in spatial models for which there is little or no training data to use in classification but there is sufficient knowledge to specify a linguistic model that is to be used to make predictions in this study were classified and predicted the environmetal vulnerability of coastal areas. The imprecision of characterized classes of environmental vulnerability in coastal areas are tied to linguistic factors (high, low, medium). Therefore boundaries between geography and between classes are difficult to characterize as they do not have sharply defined threshold values. Malczewski (1999) suggested that in such cases the views of a number of expert decision makers can be used to classify the training data cells.

The conventional probabilistic classifiers used in GIS are not always appropriate. These classifiers are based on a range of untenable assumptions about the data, for example that each class is assumed to have normally distributed data (Foody, 1995). Henper et al. (1990) and Schalkoff (1992) considered the use of an alternative approach to develop computational intelligence based classifiers, such as applying artificial neural networks, which are useful for their independence of assumptions on data distribution and their ability to use small training sets. Computational intelligence based classifiers have been shown to classify data more accurately than conventional classifiers when a small training set is available, (Foody, 1995).

The nature of an ideal training for neuro-fuzzy systems is dependent on the aim of the training stages, (Foody et al., 2006) and the accuracy which is largely dependent upon the training data provided (Kavzoglu, 2009). Several authors suggest the use of a minimum of 10 to 30p cases per class for training, where p is the number of variables used in remote sensing wavebands (Foody, 2006; Mather, 2004; Piper, 1992; Van niel, 2005). In the present study, training sites for environmental vulnerability were manually classified using expert opinion, into four vulnerability categories, based on a minimal sized training dataset. Although this approach may limit the applicability of conventional statistical classifiers, the use of 9 to 11 cases per class for the classification performed well in this study, illustrating the effectiveness of training neuro-fuzzy systems with small training sets.

Nauck and Kruse (1999) suggested that the same guidelines for selection and preprocessing of training data which enhances the accuracy for neural networks can be applied to neuro fuzzy systems. The learning algorithm NEFCLASS can provide good results for classification problems and Nauck and Kruse (1999) compared NEFCLASS results with those from other classification techniques, statistical and computational intelligence methods (e.g discriminant analysis, artificial networks and decision tree) obtaining  similar results. Ghosh et al. (2009) used a neuro- fuzzy technique to classify a remote sensing image and noted that the ability of learning with a small percentage of training samples could be made applicable to problems with large number of classes and features. Dixon (2004) applied a neuro fuzzy classification scheme to assess the vulnerability of nitrite contamination of soils with GIS. In this study Neuro-fuzzy classifiers have demonstrated an ability to derive classification of coastal areas using minimal training sets, using the same methodology of Dixon (2004). This is the first study of this kind and the approach may provide better scientific understanding and open a new route for management under uncertainties and data scarcity, a common situation in environmental spatial models.

The multivariate technique used in accuracy assessment, the Kappa Index of Agreement, has been used previously by Ghosh (2009) for testing neuro-fuzzy classification. The overall value for the calculated Kappa index of agreement for the present study was high at 81%, suggesting strong agreement (Landis and Koch, 1977). The overall accuracy, indicated by the recognition rate R = 85.71%, also represents a good agreement within the classification.  The accuracy among classes classified from the users and producers information varied from R = 77 % to 100%. The producer's accuracy shows the the classification performance for the GIS cell of a particular class, the user's gives the probability that the cell actually belongs to that class. Lowest user accuracy was found for class 4 with only 77% of the cells of correctly classified. This was probably due to the low number of samples allowing one error to modify the percentage considerably. The considerable number of cells misclassified  in class 2 and class 3, was probably due to the experts finding these more difficult to classify whereas the  extreme classes were more easily differentiated.

The estimation of separability was performed to assess the difficulties of class separation problems and the inter-class values for the Separability Indices confirm that examples selected for classes are numerically close, indicating that whilst some classes are quite distinct from each other, others are extremely close and there is difficulty in discriminating between them. The two training data sets used did not follow the assumptions of multivariate normality, for this reason the Bhattacharyya and Jeffries-Matusita Distance indices were used. Both estimate the probability of correct classification (Kavzoglu and Mather, 2002), and are more appropriate when the probability distribution of the classes is broad (Kailath, 1967). As far as we are aware, this study is the first to use these inter-class separability indices to test neuro fuzzy classification. These indices were used to estimate the degree of closeness of the training data classes before the classification system was selected. The inter-class separability indices can be used as indicators for possible confusion in order to avoid or select data set to included in a training set, however they do not give any clear indication of individual class accuracies as a consequence of the classifier (Kavzoglu, 2009).

## 6.7 Conclusions.

This study has shown that Neuro-fuzzy classifiers can provide a supervised, hard classification of the coastal environmental vulnerability using minimal training sets, defined by environmental experts through meetings and interviews. The use of training data sets in coastal environmental problems is an innovative approach that could provide a better scientific understanding and open a new route for management under uncertainties and data scarcity. The inter-class separability indices, performed on the two training data sets to assess the difficulty of the class separation problems, accurately estimated the degree of closeness and potential confusion between particular classes, prior to selection of the classification system. Further evaluation and analysis of the quality of the classification achieved showed the high overall accuracy (Recognition Coefficient), and moderately high agreement (Kappa Coefficient of Agreement).

## 6.8 Acknowledgments.

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# Chapter 7 General discussion.

The aim of this study was to develop a predictive neuro-fuzzy classification technique to classify coastal environmental vulnerability for salmon cage aquaculture. This was accomplished by using a new approach to derive fuzzy classification rules from a set of labeled data (training sites). A 3D hydrodynamic model coupled to a particle-tracking model is applied to study the circulation patterns, dispersion processes and flushing and residence time in Mulroy Bay, an Irish fjord. These models provided spatial and temporal information and helped to determine the influence of winds on circulation patterns. The final products, environmental vulnerability maps are achieved by combining predicted and real relevant environmental parameters in marine fin fish aquaculture. The output will be an environmental spatial model for application in coastal areas intended to facilitate policy decision, taking into account the intrinsic characteristics of the target area.

Regions of restricted exchange are traditionally preferred sites for human settlement and aquaculture and their ecosystems and consequent human use may be at environmental risk (Tett et al., 2003). Fjordic environments that hold the majority of the world salmon production are, in general, vulnerable ecosystems which readly become subjected to environmental strains because the residence time of anthropogenic derivatives is significantly higher than in the open ocean. For this reason this study has improved our understanding and modelling of physical processes relevant to determining assimilative capacity of aquaculture in the study area.

Mulroy Bay is an extremely sheltered, narrow inlet situated on the north coast of Co. Donegal. The surrounding lands are preferred sites for housing, while the waters are used for fisheries, aquaculture, navigation and recreation. All these activities increase the nutrient and pathogen loading and may increase the risk of eutrophication and environmental problems, which may be intensified by poor water exchange. The area was selected for several reasons, primarily aquaculture is intensively practiced within the bay, with up to 16 operators currently licensed for mussel, oyster, clams, scallop, abalone and atlantic salmon productions, secondly several aspects of water quality and hydrology were measured throughout Mulroy Bay since the Institute of Aquaculture (University of Stirling) began its annual monitoring surveys in 1986 and finally the varieties of environments provide a range of different areas to classified the environmental vulnerability.

The study followed the recommendations of The Assimilative Capacity Working Group, (ACWG, 2004) that recommended to improve our understanding and modelling of physical processes, in order to simplify and parameterise them for inclusion in biological and biochemical impact models at scales relevant to determining assimilative capacity of aquaculture. Tett et al. (2007) and Black et al. (2008) suggested the necessity to improve the existing models for assimilative capacity and benthic impact in aquaculture. Additional use of these water-based resources to expand existing or develop new aquaculture production will increase this risk further if not properly managed. Monitoring of the environment for this risk will only allow *post hoc* management after impact has occurred, enviromental models that can simulate "what if" scenarios are still needed.

The use of 3D hydrodynamic models and particle tracking models embedded in a GIS could partially fill these gaps. This study has demonstrated that this approach could be an effective predictive and management tool to model potential impacts and thus identify risks of aquaculture development or to locate or relocate activities in order to minimise these impacts and to adopt best practice for development and regulation. The study assessed the main hydrographic characteristics of the vulnerability areas to be polluted by aquaculture activities and the results from the hydrodynamic model have been incorporated into GIS to provide an easy-to-use graphical user interface for interrogation of results in 2D (maps), 3D and temporal animations. The first animation of an eddy that affected several aquaculture areas has been simulated and recorded. The sensitivity to waste of the water or sea bed at particular farm site, depends on ecohydrodynamics conditions at and around that site.

The spatial scale on which aquaculture can impact depend on a combination of nature of the pressure, the dispersion and the response time for the impact (Tett, 2008). Tett noted the importance of the spatial and temporal components and that the intrinsic characteristics of the area play an important role in the environmental problems in aquaculture. The combination of GIS with the hydrodynamic models integrated these two main components providing enhanced tools for the enviromental management of aquaculture.

Environmental vulnerability is concerned with the risk of damage to the natural environment and the susceptibility of water resources to pollution by various activities and contaminants. The suitability is considered a key factor if success is to be achieved and a sustainable aquaculture industry is vitally important as it has influence in the economic viability, running costs, production and mortality factors (Perez, 2003).

The term ‘sustainability’ is generally used to indicate the limits placed on the use of ecosystems by man. In this study a new approach to "sustainability" was introduced with a strong consideration of the spatial and temporal components in aquaculture. The simultaneous consideration of both suitability and the environmental vulnerability developed in this study can define sustainability in the spatial conceptual sense that a sustainable or an optimised marine system includes **maximum coastal suitability and minimum coastal vulnerability** (Fig 7.1).

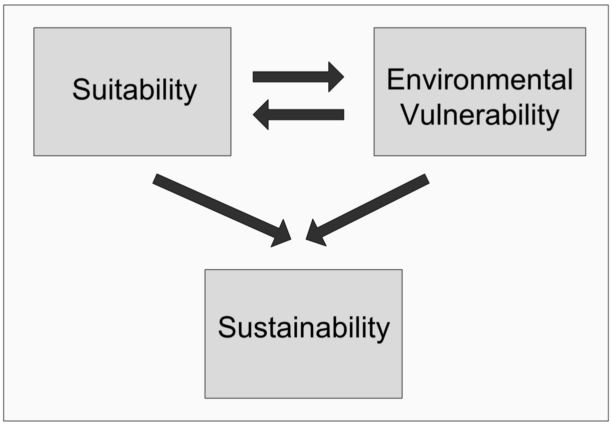

**Figure 7.1. General scheme of the coastal use and management sustainability through the simultaneous prediction of coastal suitability and coastal vulnerability as can be considered in the coastal evaluation process.**

This study appropriately classified coastal areas with high spatial resolution into areas of different levels of environmental vulnerability to a range of activities and is therefore a useful tool in identifying locations where such activities have a higher risk of contaminating the marine environment and assessing the suitability in an acceptable form. There is scope for further work on the use of the Oxygen Depletion Index and the simple waste dispersion distances in the future.

Most of the aquaculture environmental problems have obvious spatial and temporal dimensions. Environmental modelling for aquaculture can be addressed by spatially distributed models that describe environmental phenomena in one to three dimension and the phenomena modelled can change in time. The Scottish Environment Protection Agency, SEPA, suggest that a 15 days or longer data set is the most useful and this time period was selected for parametirisation of models (SEPA, 2005). It would be possible to extend this time period, although the data files created would be massive and become difficult to manage, store and manipulate. The 15 day period provided a good approximation of water circulation, although for the tidal residual current, for flushing time and residence time the period was extended over 20 days.

Three scales for impacts due to nutrient discharges have been proposed (Fig 7.2) by the UK Comprehensive Studies Task Team (CSTT, 1994). Zone A is where the water volume and sediment area immediately influence by a fish farms, Zone B represents a region of restricted exchange and Zone C represents the boundary conditions. Most studies of environmental problems and impact focus on Zone A, and this study tried to fill this gap.

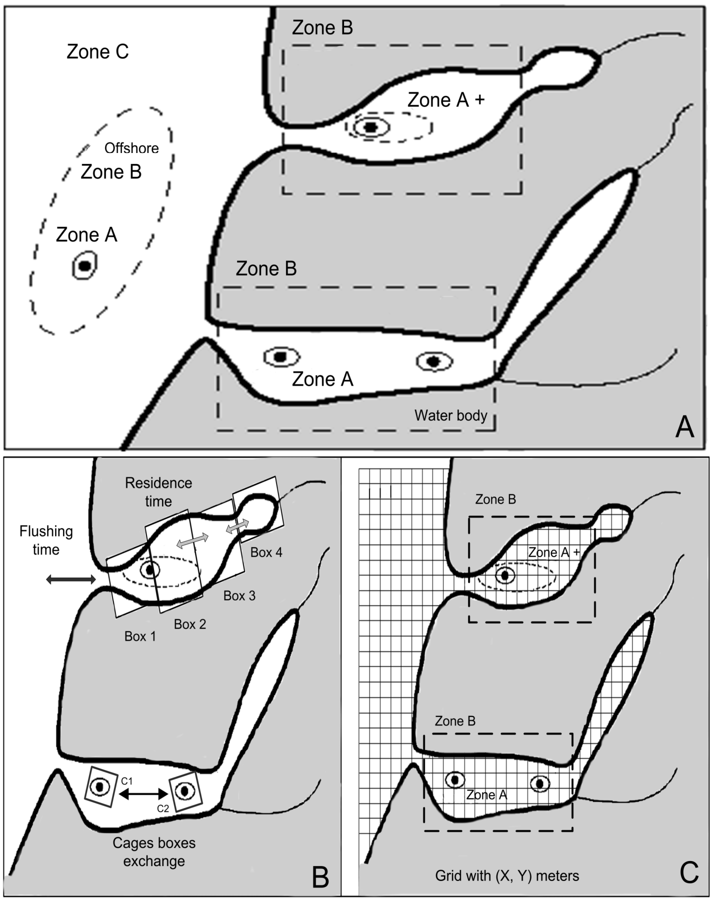

**Figure 7.2. The scales for impacts due to nutrient discharges proposed by the UK Comprehensive studies task team (CSTT) modified by the author.**

Using the scales from CSTT (1994) (fig 7.2a), a series of indicative models have been developed at a high spatial resolution (50 x 50 meters) and with five vertical layers. This study represents a new innovative use of model capabilities, and is the first study using hydrodynamic and particle tracking models simultaneously. The particle tracking model determined the time-scales of critical physical processes such as the flushing and residence time (Fig 7.2.b). The boxes determined the exchange and interaction among waters volumes in the surrounding and whole study area. Using the time-scales of critical biochemical processes in relation to the residence time, accumulation of nutrients and chemical discharge can be traced within the boxes and the final water exchange with the ocean can be better understand.

This study is the first of its kind demonstrating the interchange of water volume between salmon cages (Fig 7.2b). It is clearly important to consider the inter-relationship among them and to be able to identify such areas and modeling scenarios for environmental management because nutrient, waste dispersion and potential disease transfers from the cages may affect adjacent sites.

3D hydrodynamic modelling provided extractable 3D spatial and time series information in every cell in the grid (Fig 7.2c) on the key variables governing the dynamics of marine coastal areas and the transport and fate of pollutants in the near and far field and offshore cage marine environment. The general flow circulation was characterized by several residual tidal eddies, with a clearly wind-driven scenario. This study demonstrated the strong influences of wind forcing on circulation patterns and flushing characteristics of this restricted region.

Henderson et al. (2001) noted the potential for, and recommended the use of modeling in aquaculture activities. However, any modeling process may give false or inaccurate predictions, and complex environmental processes can be oversimplified and thus there are risks in applying modeling approaches to any environmental decision making process. A rigorous statistical testing of the sensitivity, calibration and validation of the model was also performed with the data available, although the numerical modelling was challenging due to scarcity of information for 3D model parameterization.

Creation of a 3D hydrodynamic model can be an expensive task, requiring costly computers and software, fieldwork and instrumentation for acquisition of data over a considerable time, as well as considerable expertise (Andrefoutet et al., 2006). However, the future possibilities to link with other kind of models and the benefits accruing from an aquaculture spatial decision support tool are also high. In order to reduce costs in this study open source scientific software and previously acquired data sets have been used. MOHID and NEFCLASS are freely available to the scientific community and several important aspects of water quality and hydrographic surveys were measured previously by the Institute of Aquaculture.

GIS applications in coastal and aquatic environments and Integrated Coastal Zone Management (ICZM) are still in their development (Kapetsky and Aguilar-Manjarrez, 2007; Dempsterand Sanchez-Jerez, 2008). Geographic Information Systems, GIS, defined as computer systems for entering, storing, manipulating, analysing and displaying geo-referenced data, are a powerful tool for modelling in aquaculture. GIS can be applied by combining data layers and exploring the relationship between them and constructing complex models, making the environmental management process more efficient and less time consuming. Perez (2003) suggest that GIS is only as good as the data sources and conceptual models on which they are based. Using GIS added the advantage of integrating a wide range of data and information in different compatible formats and in this study data was available in the form of nautical charts, paper maps, tables and field surveys. Most of the primary data came from reliable sources, such as national institutions with reliable quality standards and were integrated directly in to GIS database.

GIS has often been used as a tool only for map creation and simple database query rather than for modelling (Perez, 2003), although modelling capabilities are becoming more widely expolited. Nath et al. (2000) and Kapetsky and Aguilar-Manjarrez (2007) also noted that their use for environmental spatial decision support in aquaculture continued to be very slow and concentrated in terms of species, environment and country represented; as an example there are only two application of GIS for coastal salmon aquaculture in this case for site selection similar in spatial scale to the present study (Ross et al., 1993; Krieger and Mulsow, 1990) .

This study developed a new step forward and complementary to the approach successfully developed by the GISAP group at Stirling, who have been researching the role of GIS for aquaculture support for some years, mainly in suitability studies in relatively large areas. Kapetsky and Aguilar-Manjarrez (2007) noted that the present studies in GIS in aquaculture mainly cover relatively large areas (countries, island, etc) and considered that the main difficulty was in funding and generating data appropriate to the GIS task for this reason the spatial gaps in data still continue to be an issue.

In order to assess environmental vulnerability it was absolutely necessary to use other models integrated within a GIS. Li et al . (2000) suggest that the integration of GIS and environmental modelling has now been accepted as desirable, if not essential, for coastal management. Clearly, the integration into GIS of other sources of spatial and temporal data information from modelling, static and dynamic remote sensing and hydro acoustical remote sensing for assessing and monitoring environmental conditions still require improvements.

Real world computer applications to provide solutions require human expertise (Lukasheh, 2001). In aquaculture and decision making processes the trend is to integrate the various task of a problem. Depending on the type of problem it may be necessary to integrate the knowledge and processing required including data and geodatabases systems, visualisation tools and the decision–making models. Solutions can be derived using human expertise, expert and local knowledge and GIS model frameworks offer this possibility, Scientific knowledge has been integrated in this study, primarily through the expert classification of the training sites (supervised classification) and subsequent use of the classifiers to classified all GIS cells without the necessity of using boundaries among environmental vulnerability classes. Burgess (2001) found that the survey response rates to be around 20% in self administered questionnaires delivered by email attachments, post or web sites for interactive completion and inorder to avoid this, expert opion was gathered using structured interviews.

The basis of classification within GIS is the process of assigning cells to classes but this task is sometimes not easily achieved. Many types of ecological and environmental data use discrete categories and are complicated to integrate into classification schemes (Silvert ,1997) such as GIS classification with the final goal to produce a numerical index of ecological quality. The imprecision of characterization of classes of environmental vulnerability in coastal areas are tied to linguistic factors in which the classification boundaries and threshold limits are difficult to define, or which for various reasons can not have, or do not have, sharply defined boundaries. Threshold values between classes still a concern. Perez (2003) noted that in the case of suitability scores the threshold values provided by experts with knowledge of the task are better than by using mathematical approaches.

Fuzzy selection procedures should be included in environmetal models if for no other reason than because they are much less sensitive to errors or missing values in the data than the use of crisp discrete selection, (Morris and Jankowski, 2009). The disadvantages are the psychological and cultural prejudice that many people hold in favour of crisp systems or mathematically precise models and the issue of dimensionality which inevitably restricts fuzzy models to systems that can be characterised by few variables. This study used a neuro-fuzzy classifier with asupervised classification method. This had several advantages, the principal one being the use of "vague" knowledge about environmental class boundaries. However the principal problem is the classifier sensitivity, and sensitivity analysis showed a considerable level of variation in the final classification scene. Malczewski (1999) suggested that in a multiple decision maker situation, in this case using several experts to classify the training data cells, the relative importance of criteria varies among people, and the required structured interview process can be a very time consuming task. For this reason a minimum training data set was considered. The soft computing classifiers have been shown to classify data more accurately than conventional classifiers when only a small training set is available (Foody, 1995). In this study we used small training sets and this may limit the applicability of conventional statistical classifiers.

The environmental vulnerability scores vary from 1 to 4, with 4 being the most vulnerable and 1 the least. Other studies using suitability scores have used 1 to 16, 1 to 8 and 1 to 4 (Aguilar-Manjarrez, 1996; Krieger and Mulsow, 1990; Perez, 2003; Ross et al.,,1993; Salam, 2000). Scoring systems with few choices are easier and more intuitive to use, whereas with scoring systems with many classes, such as 1 to 8, the uncertainties may increase considerably and the expert may not be able to properly differentiate 8 levels of environmental vulnerability.

This study is the first of its kind to include a statistical comparison between vulnerability scores and a significant product of aquaculture waste (nitrogen concentrations in sediment under the salmon cages) showing that the final model gave a good correlation between predicted environmental vulnerability and sediment nitrogen levels.

Meaden (2004) noticed that further progress is required in developing 3-D and 4-D GIS along with appropriate data storage and modeling structures. There is scope for further work in this area, incorporating more marine water column and sea bed data and the assessment of environmental and management parameters in 3-D to 5-D in GIS as well as making such data available via Internet Map Servers (IMS). These capabilities offer the possibility of combining spatial data with layers of spatial information from other sources and models as well as the possibility of integrating the results with other data sources such as marine water quality, aquaculture bio-economic models, social and economic aspects and communications and security of the study area to develop in the future an integrated ecological approach to aquaculture activities. Overall, using neuro-fuzzy methodologies embedded in 3D Hydrodynamic and particle tracking model and GIS is an innovative approach that could provide a better scientific understanding and open a new route for management under uncertainties and data scarcity.

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## Apendix 1. Questionnaire used with experts for classification of zones.

| Depth (m) | Average (m/s) | Quiescent % | Bottom type | Stratification | Oxygen DI | Dispellet (m) | High Vulnerability | Medium/High Vulnerability | Medium/Low Vulnerability | Low Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|
| 28.43 | 0.01 | 72 | fine sand | HIGH | YES | 2.75 | | | | |
| 11.35 | 0.09 | 07 | medium sand | HIGH | NO | 4.53 | | | | |
| 9.06 | 0.03 | 93 | fine sand | HIGH | NO | 0.71 | | | | |
| 10.31 | 0.02 | 42 | medium sand | HIGH | YES | 1.66 | | | | |
| 24.69 | 0.03 | 41 | medium sand | HIGH | YES | 4.36 | | | | |
| 30.35 | 0.02 | 48 | medium sand | HIGH | YES | 4.72 | | | | |
| 37.64 | 0.02 | 58 | medium sand | HIGH | YES | 5.14 | | | | |
| 19.86 | 0.13 | 07 | coarse sand | HIGH | NO | 10.41 | | | | |
| 16.17 | 0.07 | 18 | medium sand | HIGH | NO | 4.62 | | | | |
| 11.12 | 0.41 | 02 | very coarse sand | NO | NO | 18.17 | | | | |
| 15.46 | 0.10 | 10 | medium sand | YES | NO | 6.51 | | | | |
| 19.22 | 0.07 | 12 | medium sand | HIGH | NO | 5.82 | | | | |
| 27.93 | 0.08 | 20 | coarse sand | HIGH | NO | 9.98 | | | | |
| 10.00 | 0.02 | 56 | fine sand | HIGH | YES | 1.30 | | | | |
| 12.08 | 0.10 | 06 | medium sand | YES | NO | 5.10 | | | | |
| 17.77 | 0.49 | 02 | very coarse sand | YES | NO | 36.55 | | | | |
| 17.12 | 0.26 | 02 | very coarse sand | YES | NO | 21.02 | | | | |
| 9.52 | 0.11 | 06 | medium sand | YES | NO | 4.40 | | | | |
| 10.07 | 0.16 | 02 | coarse sand | YES | NO | 6.85 | | | | |
| 10.08 | 0.15 | 04 | coarse sand | YES | NO | 6.61 | | | | |
| 15.44 | 0.13 | 06 | medium sand | YES | NO | 8.22 | | | | |
| 13.01 | 0.37 | 01 | very coarse sand | NO | NO | 22.21 | | | | |
| 19.88 | 0.09 | 17 | coarse sand | YES | NO | 7.22 | | | | |
| 12.08 | 0.07 | 16 | medium sand | YES | NO | 3.83 | | | | |
| 10.18 | 0.37 | 02 | very coarse sand | NO | NO | 14.35 | | | | |
| 9.03 | 0.44 | 01 | very coarse sand | NO | NO | 15.66 | | | | |
| 29.26 | 0.02 | 50 | medium sand | HIGH | YES | 4.98 | | | | |
| 9.03 | 0.45 | 02 | very coarse sand | NO | NO | 16.17 | | | | |
| 12.86 | 0.52 | 01 | very coarse sand | YES | NO | 30.08 | | | | |
| 30.00 | 0.01 | 55 | medium sand | HIGH | YES | 4.13 | | | | |
| 15.24 | 0.29 | 00 | very coarse sand | NO | NO | 19.67 | | | | |

# Appendix 2. Animations refered to in the text.

Thes anmations are provided as *.gif files on an accompanying DVD. To reproduce the GIF animation, open it with Microsoft Internet Explorer.

**Animation 1.** 3DMOHID allows several options for the horizontal and vertical discretization. To illustrate the Sigma coordinates the animation shows a slice3D of 5 vertical layers. In this application a 3D model forced with tide and wind was implemented at the open boundary.

**Animation 2.** A modelling scenario showing several slices (x,y) coordinate in 3D was used which defined water current from areas within the bay.

**Animation 3.** A modelling scenario showing a slice (x,z) coordinate in 3D.

**Animation 4.** A modelling scenario in 2D was used which defined water movement from areas within the vicinity of fish farms within the bay. The model used real wind data and the arrows show the direction and the speed of the current

**Animation 5.** A Lagrangian method was used to study the transport and flushing processes. Instantaneous massive releases of 15000 particles were colour coded based on their initial positions from key boxes are modelled to analyse of the ocean- fjord exchange characteristic.

**Animation 6.** To illustrate the mixing of the volume of water from the cages, the particles in different cages positions were colour coded based on their initial positions. A particle tracking model simulates the instantaneous massive release of 4000 particles representing discharge from fin-fish cages.