GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Thesis submitted for the degree of doctor of philosophy

by

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Declaration

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

Signature:

Signature of Supervisor:

Date:

A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Abstract

Scotland's coastal environment has many areas which are potentially suitable for sustainable aquaculture development. However previous studies have shown that aquaculture may have a detrimental impact on sensitive environments. The main objective of this study is to develop a holistic management tool for sustainable coastal marine aquaculture in the Western Isles of Scotland through development of a multi-faceted holistic model that allows consideration of sensitive environments. As the Scottish Government promotes better collaboration and integration of all involved in coastal zone governance (Baxter et al, 2008) this study illustrates the benefits to be gained from harmonized management of information in a Geographical Information System. GIS models are strong support tools designed to aid decision-making. The main strengths are that GIS can generate easily understandable visual displays of results which are based on robust models capable of incorporating vast amounts of spatial data and which can be predictive and can simulate future coastal environment scenarios. Within this study it is demonstrated that GIS-based models can successfully manage and manipulate a wide range of datasets that are essential components in the determination and management of suitable aquaculture locations.

The GIS decision support tools evaluated and integrated in this study were based on four main sub models. These were Cage Site Suitability, Particulate Dispersion, Sensitivity Biodiversity Indicators and Visual Landscape Capacity. Exploration of a combination of these sub-models into an overall decision support system was also completed. All sub models developed were flexible, instrumentally coherent and communicatively balanced for the management and planning of the coastal environment .

A sub-model was designed to evaluate and optimize the location of marine cage systems. This required development of data layers and modelled sub-components relevant to the important environmental and engineering factors affecting cage designs which included wave climate, bathymetric and substrate profiles. Three cage types were explored; those designed for sheltered, semi-exposed and exposed areas. These environmental factor layers were combined through weighting and Multi criteria evaluation consideration for each cage type. The resulting three sub-models indicated that while the archipelago has

quite restricted development potential for cages designed for sheltered environments (91km^2), there is a limited development potential for cages designed for semi exposed environments (1543km^2) and an optimal potential for aquaculture development with cages designed for exposed environments (3103km^2).

The greatest potential environmental impact from aquaculture comes from particulate dispersion. Currently, assessing footprints of effect from fish farms is carried out on an individual site basis mostly at ten metre resolution. The sub-model successfully developed in this work resulted in a partially validated multisite particulate sub model at one metre resolution which implemented maximum current velocity as the friction/force image. The sub-model was run on a range of coastal loch fjord systems and demonstrated the variation in particulate dispersion patterns in each fjord system. In all the fjord systems modelled, even where farm sites are close neighbours, there appears to be minimal interaction in the particulate dispersion. While the particulate sub-model is effective and rapid to deploy for multiple sites, it requires further development in order to incorporate the quantitative aspects of particulate dispersion.

Aquaculture biodiversity sensitivity indicators were evaluated and five main sub-components were developed; Species sensitive to Aquaculture, Endangered species, Species important to the Western Isles, important spawning and nursery areas and Protected Areas. The sub-model was constructed by combining these layers through weighting and Multicriteria evaluation. The outcomes indicated that within the study area there are 1168km^2 (4% of study area) which are highly sensitive to aquaculture activity, although 20595km^2 (65% of study area) has a biodiversity that is much less sensitive to aquaculture. This sub-model, and some of its components, can operate as a “stand alone” tool or can be combined into a larger framework. Little modification and re-parameterisation would be required to enable models to be developed to cover the whole of the Scottish coastline, or other coastal locations.

Aquaculture can visually affect landscapes, seascapes and can adversely affect visual capacity of different areas. GIS was successfully applied to investigate this contentious issue. This comprehensive and flexible sub-model successfully develops Seascape and Landscape sensitivity analysis of aquaculture structures and also incorporated a novel approach to visual assessment through use of proportional assessment. Combining the sensitivity layers, 6448km^2 of the waters of the archipelago (20% of study area) were categorized as having high capacity to incorporate new aquaculture developments, whilst

3301km^2 (10% of study area) have a moderate capacity for new aquaculture structures and 1324km^2 (4% of study area) have a low capacity for new developments.

An overall conceptual framework was designed to explore two methods for the combination of the major sub-models in order to identify the most appropriate areas for sustainable aquaculture with consideration of possible conflicts including conservation issues. Initial evaluations involved the extraction of information from the component GIS sub-models into a structured database. The extracted data provides a range of information that can be used for statistical analysis and decision support, but which leaves the evaluation of the optimal siting of aquaculture at any location in the Western Isles in the hands of the database interrogator. The second method involved combining the sub-models within GIS whole considering trade offs in relation to conservation. This GIS combination of models indicated that, taking many factors into consideration, the Western Isles has 748km^2 (2.5% of study area) appropriate for aquaculture development when implementing the C315 and whilst considering the interactions with conservation areas. There were 498km^2 (1.6% of study area) appropriate for development when implementing the intermediate C250 cage types but only 15km^2 (0.04% of study area) were appropriate for development based on the LMS cage designs for sheltered environments. Both analytical approaches had strengths and weakness and clearly both need to be used in combination to maximise the benefit of the GIS model outcomes.

This study has demonstrated the ability to apply scientific rigour to spatial modelling of aquaculture problems including site suitability, biodiversity, landscape capacity and multi-site particulate dispersion. The various sub-models and their components sub-models can be stand-alone decision-making tools or combined into a holistic model which incorporates a flexible method of trade-off management. The range of GIS-based coastal analytical tools developed form the core of a decision support system that can enable the objective management of the increasing demands on the coastal zone, while having the capacity to bring together stakeholders, multiple agencies and governing bodies that are responsible for management and use of these precious and sometimes threatened resources.

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This thesis finally and completely is for my granny Ina who should have had this opportunity but never did, I only wish you could have been here to see this day and thank you for believing in me even at such a young age. To my amazing Grampy you don't say much but I always know your there for me which means so much.

For my mother you drive me crazy but your unconditional support and love has guided me through the hardest days, I am truly grateful for everything you have done for me. To my baby sister I am unbelievable proud of the wonderful women you have blossomed into. Dearest Alan thank you for always believing in me and always being the calming influence in my whirl wind of a life these past few years (LP). Alison your support, words of wisdom and cards have meant more to me than you will ever know, they were always little rays of sunshine that I carried with me everyday. Lastly faithfully Skye my shadow and companion, never once complaining as you loyally lay under my desk as I worked late into the night, I own you the biggest bone.

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Chapter 1

Introduction

1.1 General Introduction

The United Kingdom aquaculture industry has grown from its crofter roots in the 1970's to become one of the European Unions largest producers and is currently third in the world for farmed salmon. The Fisheries Research Services (FRS) collects and details all statistics relevant to the Scottish aquaculture industry and the following information is from their reports. Over eighty percent of this production occurs in Scotland and the latest production values (2007) for individual species were Atlantic salmon 129,930 tonnes, rainbow trout 7,414 tonnes, cod 1,111 tonnes, brown trout/sea trout 124 tonnes, halibut 147 tonnes and Arctic charr 6.5 tonnes. As can be seen from Fig. 1.1 the production of fish has grown up to 2003 but it has subsequently decreased in production for a number of reasons. The employment generated from the aquaculture industry is a significant support for rural economies and is estimated to generate 1,000 direct jobs. In Scotland the estimated annual farm gate value of aquaculture industry to the economy is £400 million. (Scottish Government website, 2009).

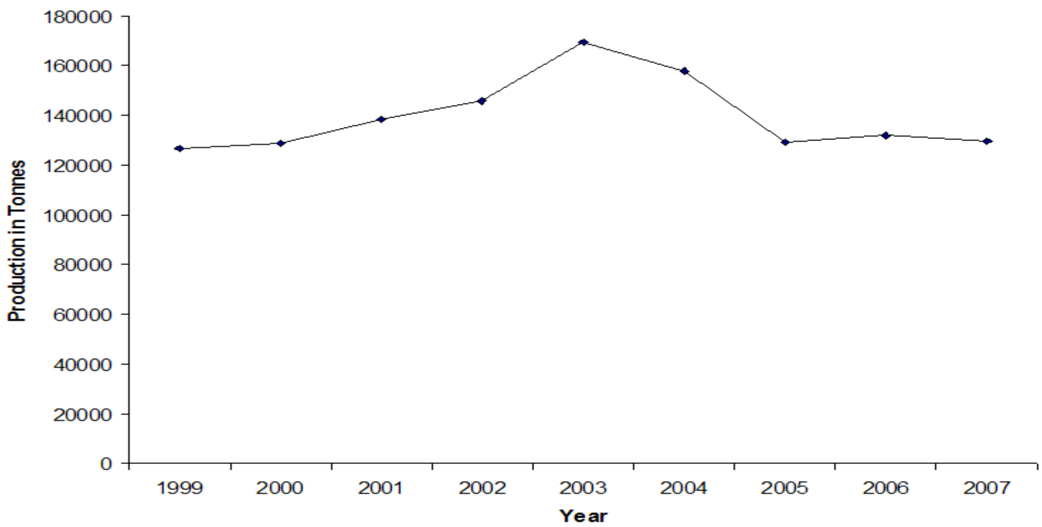

Fig. 1.1 Annual Aquaculture Production for Scotland. (FRS, 2008).

The importance of aquaculture to Scottish communities is undisputed and the Strategic Framework for Scottish Aquaculture was originally launched by the Scottish Government in 2003. The major aim was to maximize the benefits of a sustainable approach to aquaculture management. However, the original strategy has been recognized as having numerous short comings and is currently under review. In October 2007 a Ministerial Working Group on Aquaculture, announced that:

"Aquaculture is a vital industry for rural Scotland, particularly the west coast and the islands where many communities depend on its employment. The Scottish Government is fully committed to supporting a successful, competitive and diverse aquaculture industry in Scotland and with scope for the industry to grow. However, it must ensure such growth is achieved in a sustainable manner and the industry must act as a good neighbor to others who benefit from the aquatic environment."

The main areas of concern which need to be addressed in the Scottish aquaculture industry are the availability of appropriate farm sites, difficulties in securing finances, containment and fish farm escapes, control of sea lice and potential development of resistance to medicines and securing home and abroad markets (Scottish Government: Scottish Aquaculture; A Fresh Start, 2008). Now more than ever Scotland needs to consider an overhaul of its strategy for coastal aquaculture and where it is located to ensure its future.

Developing aquaculture in an environmentally sustainable manner will have many benefits. These include, reducing dependence on wild stocks (Williams et al 2000), the ability to deal with increasing consumer demand, while creating a climate of employment and ensuring long term business opportunities (Macallister Elliot and Partners 1999). The major area of concern is focused around intensive fish and shellfish farming in Scotland, with particular emphasis on its location and mode of environmental regulation. Any establishment of fish farms must apply for and be granted a license under the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR). Once granted the Scottish Environment Protection Agency (SEPA) regulates and controls the activities of the fish farm. This regulation is implemented through Environmental Impact Assessment regulations: for further details see http://www.sepa.org.uk/water/regulations.aspx.

The coastal habitats of Scotland are varied and dynamic in nature and this is reflected in the numerous designations of sensitivity to enviromental impact under the Natura 2000 programme (The Conservation (Natural Habitats, &c.) Amendment (No. 2) (Scotland)

Regulations, 2007).The potential impacts of aquaculture are wide-ranging; from direct pollution to aesthetic aspects (O'Sullivan, 1992). Environmental impacts of aquaculture, including the introduction of nutrient and chemical wastes into the environment, may have significant implications for the surrounding water and sedimentary environments, and especially on localized species and habitats (Black, 2001, Read and Fernandes, 2003, López *et al*., 2008). Furthermore, implementation of the Water Framework Directive (WFD Directive 2000/60/EC) requires the maintenance of high water quality standards taking full account of the effects of fish farming activities on chemical, biological and morphological features.

The unfavorable impacts of aquaculture are widely documented throughout the literature (Gowen *et al* 1988; Ackefors and Enell 1990; Wahab *et al*, 2003). The areas of major concern are of organic enrichment (Kawahara et al, 2009), biodiversity (Beardmore et al, 1997), landscape, seascape and visual impacts of aquaculture development (Environment Waikato Technical Report 2008/24; Grant 2006) and lack of sustainability (Naylor *et al* 2000). What is not in question is the fact that any activity will inevitably have some level of impact. However, the aquaculture industry has a vested interest to ensure that impacts are minimal. Management practices are needed that guarantee the sustainable management of coastal zones (Turner and Bower, 1999).

With the move for change by the Scottish Government and the numerous legislative powers protecting the Scottish coastline, there is a greater need for a structured approach to selection of sites for aquaculture development. Any such approach needs to have the capability to account for a varied amount of data that includes site selection, conservation and waste dispersion. In addition, development of such tools may potentially prove particularly useful in the future development of spatial tools to store and process environmental information, as required under the WFD.

1.2 Geographical Information Systems (GIS)

There is no doubt that coastal management is a complex ever-evolving issue. In order to implement best practice and technology, management tools need to be spatial, highly flexible and have the ability to be quickly reviewed and revised as new information becomes available. The biggest drive forward in marine environmental policy came during 2008 with the introduction of the Marine Strategy Framework Directive 2008/56/EC (OJ L164, 25/06/08). This Directive strongly promotes the need for all EU members to establish a framework to protect the marine environment and which leads to an overall improvement in its status. The objective of the Marine Strategy Framework Directive

(MSFD) requires that, by 2020, there will be improvements in the ecological health of our seas and for this to be achievable there must be substantial assessments of the current sea states and determination of the issues encountered in the coastal zones of each member state. The Fisheries Research Services (FRS), Scottish National Heritage (SNH) and Scottish Environmental Protection Agency (SEPA) collaborated in 2007 to assess the state of Scotland's Sea's (Baxter et al, 2008) The content and purpose was to review the current state of knowledge and highlight gaps in our current knowledge of Scotland's seas. The overall findings from the study indicate that the Scottish seas are changing in a way that may cause a disturbance in the distribution and abundance of marine species and which could lead to changes occurring in the Scottish coastlines. The main aim of this project was to develop a fuller report on the State of Scotland's Seas which should be published in 2010. Once the state of our seas has been determined the directive expects the application of initiatives to maintain, improve and protect the marine environment in a "good ecological state". One problem that is currently experienced when governing the marine environment is the fragmented approach taken by the multiple governing bodies involved and there is a greater need for an integrated approach that steps away from this fragmented decision making which can lead to conflict and environmental degradation.

The MSFD also identifies the importance of unifying the aspects of policies, economics, environmental and social issues through marine spatial planning based on ecosystem principles. Both the Ecosystem Approach to Aquaculture (EAA) and the Ecosystem Approach to Fisheries (EAF) are major current initiatives of the Food and Agriculture Organization of the United Nations (Soto, Aguilar-Manjarrez and Hishamunda, 2008) which encapsulate and promote holistic and integrated development and management practices. The integrated marine planning tools that are being promoted through the MSFD and EAA are to be implemented in a spatial context through the principles of integrated coastal zone management (ICZM). This directive and its spatial approach to marine planning is the ideal framework into which the present study fits, as it provides a rational policy framework for optimal development of all aquaculture in a logical and sustainable manner.

Scottish aquaculture currently finds itself in a situation requiring an approach that can deal with great complexity and uncertainty and the current literature recommends a modelling approach in aquaculture regulation and monitoring (Henderson et al, 2001). Geographical Information Systems (GIS) provide a technology which has the capacity to address these complex issues and the strengths of GIS for optimizing marine aquaculture is in no doubt (Perez, *et al* 2003), although its application in this sector has been taken up rather slowly, even with active support and promotion over the last fifteen years (e.g. Nath *et al,* 2000; also see GISAP http://www.aqua.stir.ac.uk/aqua/GISAP and FAO GISFish http://www.fao.org/fi/gishfish/). Currently in the UK marine environment, government of national and regional policies is inconsistent and rarely employed uniformly. GIS provides the ideal platform for integrating regional and national policies in a coherent manner which is in line with the Marine Strategy Framework Directive.

The implementation of well-structured common GIS frameworks for marine spatial planning could enable improved information availability and better coordination of decision making across agencies while encouraging a high level of community involvement and creating mechanisms for pre-emptive conflict management. Such studies based on environmental and system considerations have been shown to be an excellent tool for detailed facility location, once a preliminary choice of site has been made (Ross, *et al,* 1993). In conjunction with remote sensing and direct data collection, GIS can also form the basis for continued monitoring of a site; for example, recent work has shown that dispersal of wastes from an aquaculture site can be modelled in GIS to great advantage (Corner, *et al*, 2006).

GIS model investigation scales can vary significantly and can range from very large or very small areas, with appropriately different spatial resolutions used for different purposes. GIS frameworks can be employed at a basic level which can simply be used to identify, collect and present data. Applying relatively simple environmental and resource availability models of aquaculture potential have also been explored at continental scales for Africa and Latin America, using (Kapetsky, 1994; Kapetsky and Nath, 1997; Aguilar-Manjarrez & Nath, 1998). For maximum benefit this type of informative mapping and database query should be accessible by the wider community and governing agencies. A number of national or state level investigations have been conducted successfully, based on a wide range of data on environment, infrastructure, resource availability and socio-economics (Aguilar-Manjarrez and Ross, 1993,1995a,b). These meso-scale models are particularly useful for guiding national plans, for consideration of food security issues and for investigation of conflict and trade-off between different economic activities. However, at its most advanced level, GIS provides a framework for complex spatial modelling which can be used to determine suitability zones, protection zones and multi usage zones, within the guidelines and polices for the UK or elsewhere.

The strengths of Geographic Information Systems (GIS) for optimizing marine aquaculture are in no doubt (Perez *et al* 2001). The rapid advancement in variety and resolution of digital, primary data that are becoming available has greatly facilitated the harnessing of GIS models. Numerous studies have been published on the application of GIS and remote sensing in aquaculture (Kapetsky *et al* 1988: Aguilar-Manjarrez and Ross 1995: Aguilar-Manjarrez and Nath, 1998; Arnold *et al* 2000; McLeod *et al* 2002; Rowe *et al* 2002 and Salam *et al* 2003). Furthermore GIS has been used successfully in the development of aquaculture management systems under a variety of conditions and locations including Mexico (Aguilar-Manjarrez and Ross, 1995), Bangladesh (Salam *et al*, 2000; Hossain *et al*, 2009) and Tenerife (Perez *et al*, 2005). FAO has been instrumental in promoting the importance of GIS for aquaculture and fisheries management and planning (Meaden and Kapetsky, 1991; Kapetsky and Nath 1997: Kapetsky and Chakalall 1998; Aguilar-Manjarrez and Nath 1998; Graaf *et al*, 2003; Jenness *et al*, 2007; Kapetsky and Aguilar-Manjarrez, 2007). The major finding from all these studies is in the demonstration of the ability of GIS to deal with the complex issues, which are also relevant to Scottish aquaculture.

One of the major difficulties for the implementation of GIS is the selection, collection and digitizing of spatial information and conversion into formats which can be used by the GIS (Tseng *et al*, 2001). However, the rapid advancement in variety and resolution of digital, primary data that are becoming available at low or no cost has greatly facilitated the feasibility of developing more complex GIS models. The implementation of GIS as a tool for integrated management of Scottish aquaculture has been slow. It is currently mainly used as storage system, providing acces to spatial information. These inspectable databases and maps, for example those for landscape characterization (SNH/CA, 2002), fall short of truly maximising the actual capabilities of GIS. GIS systems have a variety of analytical, statistical and modeling tools that can be utilized to manipulate spatial datasets and which can be developed into decision support systems (DSS) thus transforming the system well beyond a simple database query. Taking the current baseline of inspectable databases and creating a framework that harnesses the strongest modelling and DSS components of a GIS system could provide impressive capabilites for the long term sustainablity for Scottish aquaculture. The ultimate advantages would include its simplicity, flexibility, the ability to incorporate vast amounts of spatial data, including quantitative and qualitative information, and the capacity to analyze and model multiple outcomes and to consider trade offs.

1.3 Aquaculture Development Management Strategies

1.3.1 Integrated Coastal Zone Management

An area designated for aquaculture should have the ability to be used in an environmentally and economically sustainable manner for an indefinite period. The development of aquaculture activities should also be predicated on the notion of environmental resilience which is the future capacity of a natural system to recover from disturbance (OECD, 1998). This should be the definitive aim, not only for producers, but also for statutory regulators. The concept of Integrated Coastal Zone Management (ICZM) was created to replace previously narrowly focused management and authorization practices on a project by project basis (Margerum and Born 1995; Cicin-Sain and Knecht,1998). ICZM applies the eight key principles of 1: taking a broad holistic approach, 2: on a long term perspective, 3: using adaptive management, 4: applying specific solutions and flexible measures, 5: working with natural processes, 6: participatory planning, 7: support and involvement of all relevant administrative bodies and 8: using a combination of instruments to achieve sustainable development of coastal areas (COM/00/547, Margerum and Born, 1995; Vallega, 2001).

It is a proactive approach with the ability to address potential conflicts at the early planning stages of any proposed new developments. ICZM for a particular area should be a well designed continuous, interactive, adaptive and participatory method that consists of a number of phases.

Integrated Coastal Management, as viewed by the World Bank (2002), seeks to:

"maximize the benefits [to society] provided by the coastal zone and to minimize the conflicts and harmful effects of activities on social, cultural and environmental resources through …….. an interdisciplinary and intersectional approach to problem definition and solutions" involving *"a process of governance that consists of the legal and institutional framework necessary to ensure that development and management plans for coastal zones are integrated with environmental and social goals, and are developed with the participation of those affected'*.

Clearly, the GIS model framework accords very well with the concept of ICZM which is based upon the supposition that economic development and environmental management should be measured within a single integrated management framework. ICZM in its simplest form requires any coastal area to be identified as a development, protection or conservation priority. For any successful ICZM strategy the database is the key component and, clearly, GIS systems are inherently suitable because of the coherent and concise manner in which the underlying database for GIS is specified and built up. GIS databases can incorporate all of the relevant information pertaining to ICZM management and have the potential to inform policy makers in the decision making process (Fedra and Feoli, 1998; Fedra, 2008).

It is widely accepted that for coastal aquaculture to be sustainable it should be developed within an ICZM framework (Fernandes and Read, 2001; GESAMP 2001; Soto *et al*, 2008). GIS has the capability to be an essential tool that could support this framework in a holistic manner. This has recently been incorporated in EU policy initiatives with the introduction of "*An Integrated Maritime Policy for the European Union"* commonly known as the "Blue Book" (Brussels, COM (2007) 574 Final). The main premises of action are a series of proposals that offer potential benefits for marine environmental protection. Specifically, there are proposed actions on fisheries, marine spatial planning, climate change and marine research, with an overall emphasis on developing an ecosystem-based approach to management. In the Action Plan accompanying the Blue Book, numerous areas for development are proposed, the most relevant to this study being:

"Tools for integrated policy-making; New tools will be required to achieve integrated governance: an integrated network of surveillance systems (for marine safety and enforcement); maritime spatial planning (linked to Integrated Coastal Zone Management); and an EU Observation and Data Network."

The Scottish Parliament (2002a,b) have published guidelines that direct aquaculture towards the implementation of an ICZM framework for Scotland. However, to date, there has been only minimal implementation of these recommendations. Barker (2005) highlighted a significant weakness in current ICZM practices in Scotland that have restricted involvement of the community as well as a preoccupation with economic outputs and an over-emphasis on the bio-physical environment. Interestingly, GIS has the capacity to deal with an ICZM framework on a multi agency level and with a high level of community involvement. GIS is flexible, rapidly updateable and can explore multiple outcomes depending on the relevant polices and guidelines in place. Local communities will not always agree with outcomes and decisions but by allowing the process to be open and easily understandable this will inevitably reduce possible conflict in future. This is a necessary option within a well-designed GIS system.

1.3.2 Ecosystem Approach to Aquaculture Development

The Blue Book (Brussels, COM (2007) 574 Final) has an over-arching emphasis on developing an ecosystem-based approach to management. This can be directly linked to the recent developments and concepts being by driven forward by FAO which defines the need for a framework of management considering all other users and that aquaculture is developed holistically and sustainably so as to ensure that any impact on the environment is not detrimental for future users. Known as the Ecosystem Approach to Aquaculture (EAA) it aims to define and quantify the environmental, social, technical, economic and political aspects that must be incorporated into management strategies (Soto *et al*, 2008). For full implementation, these concepts require tools capable of high analytical and organizational standards. GIS is capable of this holistic analysis and organization of most of the aspects determined in the EAA. EAA is definied as "*An ecosystem approach to aquaculture is a strategy for the integration of the activity within the wider ecosystem in such a way that it promotes sustainable development, equity and resilience of interlinked social and ecological systems*". The EAA aims to be a strategy that ensures the contribution of aquaculture to sustainable development, guided by three interlinked principles:

> *Principle 1 Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity*
>
> *Principle 2 Aquaculture should improve human well-being and equity for all relevant stakeholders*
>
> *Principle 3 Aquaculture should be developed in the context (and integrated to) other relevant sectors.*

The EAA is a holistic approach that focuses on the entire ecosystem through adaptive management. The approach for this framework strongly supports the implementation of GIS for EAA planning, while also encouraging stakeholder involvement and integrative policies including, ecological, economic and social realms.

1.4 Marine Aquaculture Development

There are many areas of concern when considering any marine aquaculture development (Stickney and McVey 2002), but for this study four major topics for managed aquaculture development in the Western Isles are explored: site location, waste dispersion impacts, biodiversity analysis and visual landscape and seascape analysis.

Scotland’s current policies for fish cage site selection have been deemed inadequate and lack the strength to support sustainable development of aquaculture (Scottish Parliament 2002a,b). The major flaw is the narrow focus on carrying capacity for nutrients within management areas and embayments (Gillibrand and Turrell 1997), which is based primarily on hydrodynamic characteristics and subsequent nutrient retention in the area. Almost no consideration is given to the actual suitability of a cage structure, its engineering features and its ability to perform well in a given area and sea conditions. Furthermore, many of the criteria that are required for the Environmental Impact Assessment process are still based on considering fish farms in isolation (*Telfer et al*, 2009). To adopt a more structured approach to site location a regional overview of suitable sites and appropriate selection criteria is needed. The most effective means of achieving this is to use a single process capable of incorporating all of the data needed for determination of site suitability. Much of this information is spatial in nature and thus the most efficient method of manipulation and modelling using this type of data is to use Geographic Information Systems (GIS). This opens up the prospect of development of sub-models and decision support tools that will allow multi-site aquaculture planning and management within a coastal zone management plan.

Once an area has been determined as suitable for the farming activity it’s sustainability and resilience needs to be established and this can only be achieved by minimizing environmental impacts (Scottish Executive, 1999). Multiple wastes are potentially released into the wider environment from fish farm sites. A significant fraction is as particulate organic waste in the form of uneaten feed and faeces (Beveridge, 1996) and an important consequence of aquaculture is an environmental footprint formed by this waste organic matter. Although different opinions have been expressed about both the magnitude and type of aquaculture effects, consensus exists that the gradient of diminishing impact varies from location to location, and that in the worst case scenario the sediment environment under cages can become anoxic and even azoic (Iwama. 1991; Kara-Kassis *et al*, 1999; Holmer *et al*, 2003).

Distribution models for organic waste from aquaculture can be used to predict possible impacts on the environment (Ervik *et al* 1997; Stigebrandt *et al*, 2004; Cromey *et al*, 2008; Brigolin *et al*, 2009). These predictive models can assist environmental regulators to make informed decisions when licensing new marine fish farm developments and granting consent to discharge waste. As stand-alone tools they are extremely informative although there is a need for them to be more adaptable and capable of being integrated into a wider set of decision support tools. Waste dispersion models have been under development since the early 1990's and have evolved through a series of improvements from relatively simple spreadsheet models of particulate waste dispersion (Gowen *et al*, 1989) to more complex spreadsheet models (Telfer, 1995) to regulatory tools such as DEPOMOD (Cromley *et al*, 2002). Perez et al, (2002) adapted a spreadsheet model for implementation within a GIS framework and this was finally developed as a fully integrated GIS coastal zone model by Brooker, (2002) and Corner *et al* (2006). However, the full development and implementation of this type of model within a wide field framework requires further development.

A major consideration for any aquaculture development is biodiversity and ensuring that the activity does not come into conflict with important ecologically sensitive marine habitats. There is a need for strong, well structured tools for the conservation of priority species and this is particularly relevant when considering the close relationship aquaculture inevitably has with its environment. The purpose of identifying species distributions and further classifying habitat suitability models for the species under study here are concerned with the numerous possible conservation areas; for endangered species, species re-introductions, population viability analyses and human wildlife conflicts (Palma *et al* 1999, Breitenmoser *et al* 1999, Le Lay *et al* 2001, Akcakaya, 2001: Mladenoff and Sickley, 1998; Schadt *et al* 2002; Guisan and Thuiller, 2005; Oliver and Wotherspoon 2005; Tole, 2006). Implementing the concept of Habitat Suitability Modeling is based on the ecological niche theory (Grinnell 1917; Hutchinson 1957), where the fundamental argument is that individual species will thrive within specific ranges of environmental conditions. Developing such a model along with those already defined above would greatly aid environmental management of the coastal resource. The methods can vary greatly in their application (for a comprehensive review, see Guisan and Zimmermann 2000). Any existing models are currently implemented in a stand-alone form based upon simple indices or may use multivariate analyses with the ability to determine habitat suitability. The one main premise which underpins all such models is that prediction is based on environmental conditions.

Peterson (2006) reviewed and identified the contributions to conservation and environmental management through the method of identification of the ecological requirements of species and their limiting factors. These factors lead to the understanding of biogeography and dispersal barriers and enable the location of unknown populations and new species; the categorisation of reintroduction sites; the design of conservation plans and reserves and the anticipation of effects of habitat loss and ability to foresee species invasions. Based upon these principles, there is a clear requirement to construct habitat suitability models to identify priority marine conservation locations across the Western Isles and to consider how these may interact with present and future aquaculture.

A major emerging area of conflict for any aquaculture development is its resulting visual impact on the environment. Challenges of this kind have previously been highlighted (Opdam *et al*, 2002: Wissen *et al*, 2008 Ladenburg and Dubgaard 2009) and are becoming increasingly important as pressure on world resources and space usage increases. Any aquaculture development will have structures associated with it both on and offshore, the main components being fish cages, boats and buildings. Not only is there a direct, simple visual impact but there is also an impact on two other related distinctive environmental considerations: landscapes and seascapes. The incorporation of ecological factors into visual aspects of landscape planning has been discussed (Sheppard, 2001: Termorshuizen et al, 2007) the development of a GIS spatial model to address this need to incorporate the ecological factors is an important component of the present study.

In order to develop a GIS-based toolbox for aquaculture in the Western Isles it is important to ensure that it is capable of modelling the actual and / or future impacts of fish farms, in relation to other physical and ecological factors on environmentally sensitive parameters and areas or places of conservation interest in the coastal area of Scotland. This tool could then be further developed to extend to the whole of the Scottish coastline.

The overall objectives of this study were:

1. To construct a spatial database appropriate for analysis and modelling of marine aquaculture in the Western Isles of Scotland, principally using existing databases and available information.

2. To develop a GIS based sub-model of cage site suitability which addresses the importance of siting different types of marine cage technologies based on their physical design capabilities. This sub-model incorporates the important criteria of Currents, Bathymetry and Wave Climate.

3. To develop a particulate dispersal sub-model, wholly within a GIS environment, which is appropriate for large-scale multi-site analysis, in the form of a footprint model and requiring minimal data input.

4. To develop a biodiversity sub-model which identifies ecologically sensitive habitats and which incorporates both land and marine species of conservation concern. The biodiversity sub model aims to address the identification of sensitive areas not just for individual species but also to include habitat suitability. This sub model incorporates important criteria on protected areas, endangered species, species sensitive to aquaculture, commercial fisheries and general local habitat and species distribution of importance for the Western Isles.

5. To develop a sub-model for visual analysis and landscape/seascape assessment that enables objective and quantitative identification of potential areas of impact of any aquaculture development, using a novel approach for visibility assessing on a proportional impact level. The viewshed sub-model addresses the complex issue of visual impacts and the ability of landscapes to incorporate aquaculture developments. The process uses a digital elevation model incorporating a variety of pre-defined important viewpoints assessed over a variety of visual envelope distances. The landscape assessment incorporates landscape sensitivity values for aquaculture determined from the landscape characters and National Scenic Areas of the Western Isles. The seascape assessment incorporates seascape sensitivity values for aquaculture determined from the seascape characters.

6. To develop a holistic, multi-site decision support system based on these sub-models, and their combinations, which, through trade-off management, could allow assessment of developments over a wide area.

These sub models can either be operated as stand-alone tools if only one aspect needs to be considered. They can also be further refined by reclassifying the sub model outputs for suitability, sensitivity or capacity and then combined with other sub-models in a decision support system for environmental managers and regulators for the effective sitting and management of aquaculture systems. This type of model approach and its underlying database has the potential for substantial expansion in both geographical and information terms, allowing further sub-models to be developed for other aspects of Scottish aquaculture.

1.5 Overall Model Framework

Coastal areas are very diverse and many issues experienced are complex not only solely in terms of the environment but also in the jurisdictions pertaining to the coastal zone. Increasing pressures are being placed on the coastal environments for allocation to multiple users. Thus the key driving principles behind the sub models developed for this study are the need to develop a framework for aquaculture that is managed in an holistic environmentally sustainable manner and is also one that considers the polices and frameworks needed to drive them.

Spatial planning can provide a framework that allows management of the increasing demands on the coastal zone and can bring together multiple agencies and governing bodies that are responsible for this management. The spatial planning tools (sub-models) designed here aim to address the magnitude of complex issues encountered in the marine and terrestrial environments for aquaculture development. These sub-models have the additional ability to be combined flexibly into an overall aquaculture decision support system (Fig. 1.2)

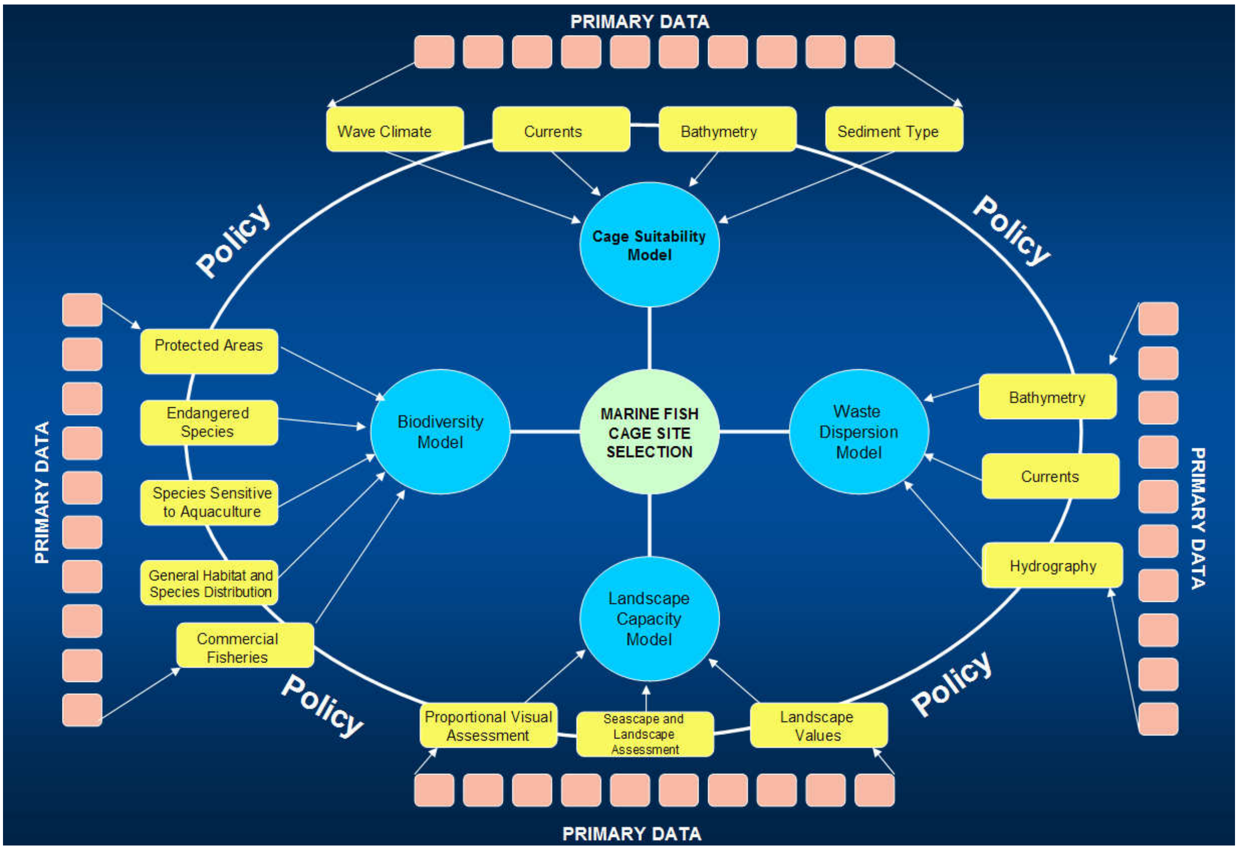

Fig. 1.2 Conceptual GIS model framework providing decision support for marine aquaculture in the Western Isles, Scotland

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A G.I.S FRAMEWORK FOR THE EVALUATION OF MARINE CAGE AQUACULTURE DEVELOPMENT IN THE WESTERN ISLES, SCOTLAND.

Chapter 2

The Study Area

2.1 The Western Isles

The chosen study area for this research was the Western Isles (*na h-Eileanan An-Iar*) also known as the ‘Outer Hebrides’ off the North West coast of Scotland (Fig. 2.1) at a latitude of 58 00º N and a longitude of 7 00º W in the north Atlantic Ocean. The Western Isles are an archipelago of islands comprised of five main islands; Lewis (*Leòdhas*), Harris (*Na Hearadh*), North Uist (*Uibhist a Tuath*), Benbecula (*Beinn na Bhadhla*), South Uist (*Uibhist a Deas*) and Barra (*Barraigh*) with a combined coastline length of 2,103km. With a total approximate length of 200km in length and at its widest point 60km across the islands are composed of gneiss rock. The main islands are relatively flat with the highest point being the Clisham peak on North Harris at approximately nine hundred metres.

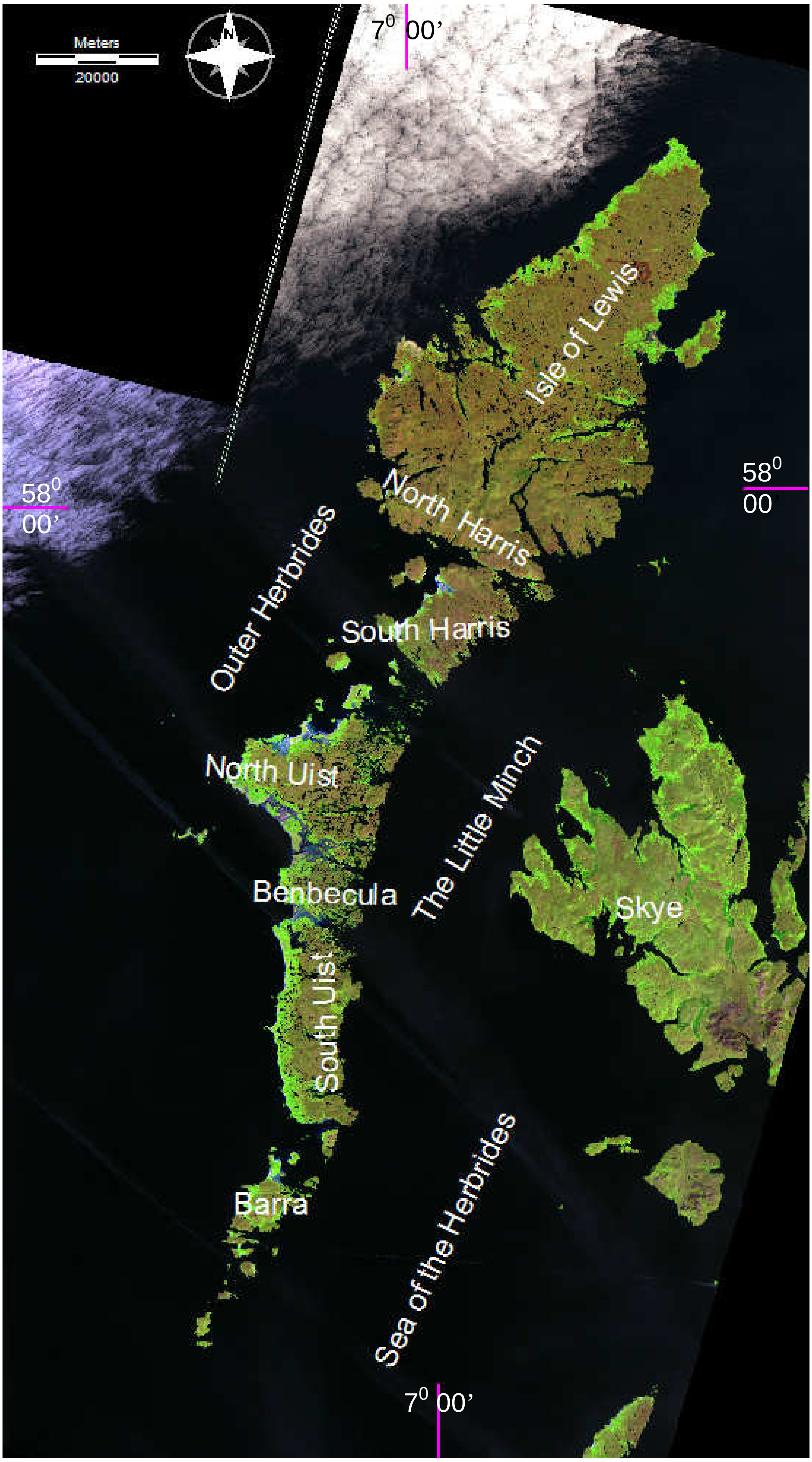

Figure 2.1 The Western Isles off the North West coast of Scotland

Climatically, the Western Isles is dominated by wind and rain and experiences very little temperature variation throughout the year with winter highs averaged at 7^{o}C and summers high averages of 16^{o}C due to the influence of the 'North Atlantic Drift'.

The islands of the Western Isles are highly characterised by their vast freshwater surface area with over six thousand lochs (Fig. 2.2). The vast coastline of the Western Isles has many sea lochs (fjords), bays and numerous small uninhabited Islands. The coastal habitats are diverse and vary in nature with numerous sites being protected under national statutes as well as many designated areas of international conservation importance being located in the region. The defined protected areas fall under different national statutes the most important ones being fifty five Sites of Special Scientific Interest (SSSI) which represent the best of Scotland's natural heritage. There are currently three National Scenic Areas (NSA) one of these covering a third of the land area of the isles designated for national landscape protection. Fifteen Special Areas of Conservation (SACs) are areas designated under the European Directive commonly known as the 'Habitats' Directive. Together with the thirteen Special Protection Areas (SPA), which are classified under the EC Directive on the Conservation of Wild Birds (79/409/EEC), commonly known as the Birds Directive, these collectively form the Natura 2000 network of sites.

Fig 2.2 Clisham peak on North Harris looking North towards Lewis and the water body is Loch Langavat © Copyright Walter Baxter.

The dominating features of the northwest and eastern coasts are the rocky cliffs and cliff top habitats, which are of considerable conservation significance as they support large seabird populations of national and international importance. In addition to the cliffs there are notable caves and sea stacks of scenic value and of major importance to the tourist industry.

Due to improper management strategies of farming the native woodlands of the Western Isles have become degraded and fragmented with very few remaining areas of significant tree cover. Where there is tree cover, species present include aspen, downy birch, eared and grey willow and rowan Fig. 2.3.

Figure 2.3 Western Isles Native woodland, from Native woodlands habitat plan, 2004.

In contrast to the minimal tree cover the coastline has large areas of sand dunes and the unique machair plains extending up to 2 km inland. The latter, along with areas in mainland Scotland has been identified by the Joint Nature Conservation Committee as the only location for this type of habitat in the world (Angus, 1999). The best untouched examples of machair are located in South Uist and North Uist (Angus, 1999). The machair habitats support internationally important breeding grounds for waders (in particular corncrakes) and wildfowl.

Numerous nationally rare or scarce plants are found in machairs including holy grass (*Hierochloe odorata*), oysterplant (*Mertersia maritima*), variegated horsetail (*Equisetum* *variegatum*) and Baltic rush (*Juncus balticus*). Some 7,964ha of machair habitats are located in the Western Isles (Angus, 1999). This amounts to fifteen percent of the total British sand dune resource. Furthermore, the second longest sandy beach in the UK occupies all of the western side of South Uist.

The Western Isles has a highly diverse range of species, mainly dominated by a wide range of bird species. Many of the important breeding grounds for numerous bird species are pesent in the isles. In complete contrast to the bird poulation, the Isles have only two native land mammals, red deer (*Cervus elaphus)* and otter *(Lutra lutra).* The Isles have a rich variety of freshwater and marine species. In 2004 the Western Isles Local Biodiversity Action Plan was begun and was aimed at the identification of important habitats and species of the Western Isles and to actively involve the local communities to enhance and protect them. Species for which action plans are in place for the Western Isles include, Great Yellow Bumblebee (*Bombus distinguendus*), Corncrake (*Crex crex*), Corn Bunting (*Miliaria calandra*), Dunlin (*Calidris alpina*) and Irish Lady's Tresses (*Spiranthes romanzoffiana*). Western Isles habitats for which action plans are in place include Broadleaved, Mixed and Yew Woodland, Cereal Fields and Margins, Saline Lagoons, Upland birchwoods and Wet woodland.

2.2 Western Isles Infrastructure

Stornoway is the major port and as such is the central point for fishing, ferries, cargo vessels and cruise liners, though there are other small harbours located throughout the islands which are also important for fishing and ferries. Ferry transport is central to the economy and island life and the island communities are solely dependent on it for supplies from the mainland. There is currently a marine traffic separation scheme north of Skye and a voluntary loaded-tanker exclusion zone in the Minches. This substantial shipping traffic along the western Scottish seaboard includes super-tankers destined for oil terminals on Shetland and Orkney.

The Western Isles is one of the least populated areas of the UK with a resident population of only 26,502 as determined in Scotland’s 2001 census. There is sparse industrial development and the two main economic drivers for the Western Isles are the Harris Tweed Company and the Aquaculture industry. Stornoway on Lewis is the main centre of the population and industrial development is concentrated in this area. The communities of the Western Isles have a strong cultural identity which is linked to the crofting roots of the isles. Also, unlike mainland Scotland, the traditional language of Scotland (Gaelic) is spoken by approximately sixty percent of the population in the isles.

Both the main fish processing companies and Harris Tweed factories are based in Stornoway. Atlantic salmon (*Salmo salar*) is the dominant coastal aquaculture species, although the introduction of halibut culture *(Hippoglosus hipploglosus*) has recently increased production. The majority of fish farms are located on the eastern coasts due to the more favourable and sheltered environmental conditions. Fig. 2.4 shows the locations of the many active fish farms in the Western Isles as well as their consented biomass categories. As can be seen, coastal aquaculture in the Western Isles occurs mainly in the larger sea lochs.

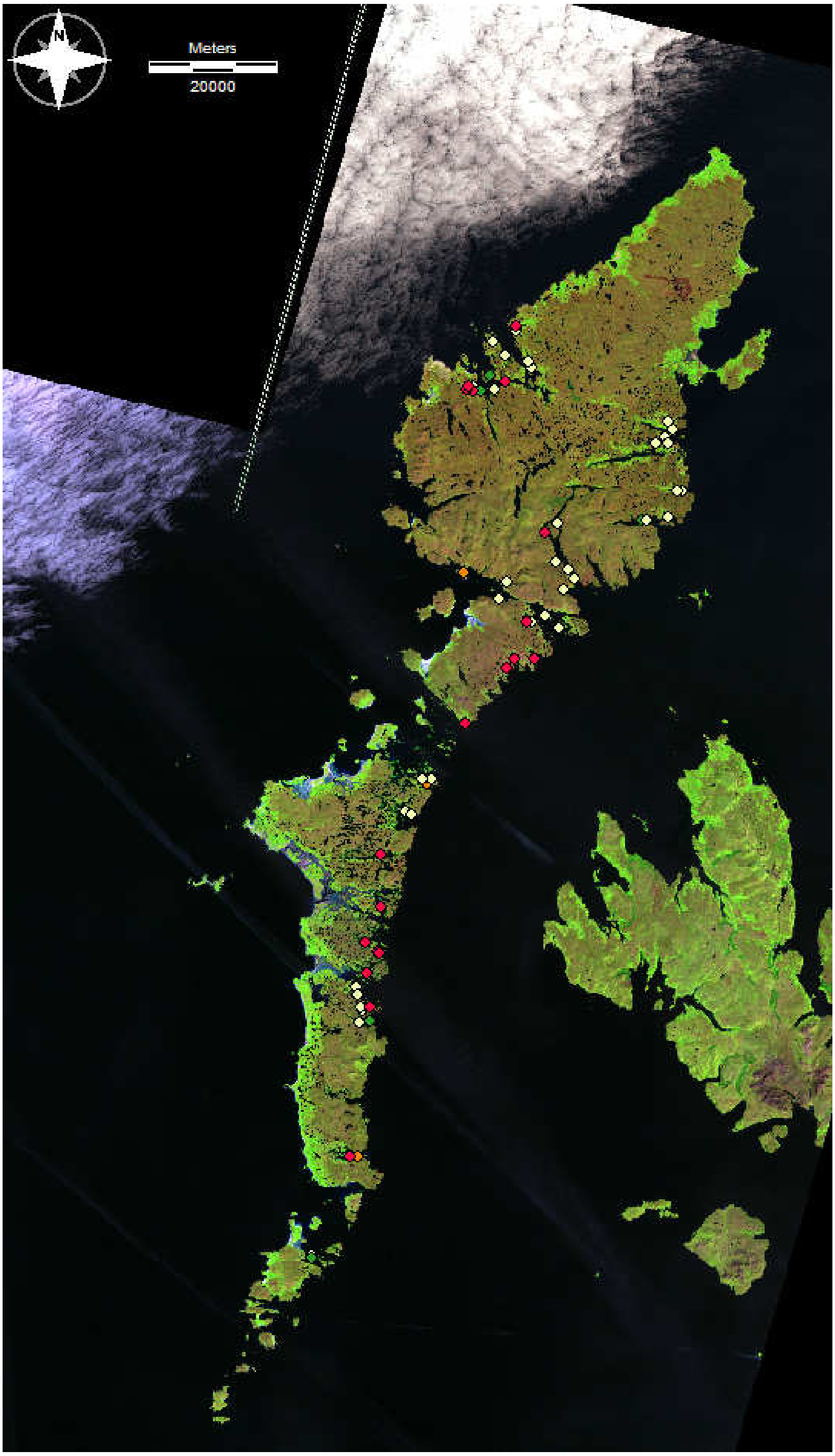

Fig. 2.4 LANDSAT ETM+ with current active fish farming areas and biomass consent for each farm.

Green = 0-500t, Yellow = 1000-1500t and Red = 1500 to 2000t.

The Western Isles aquaculture industry has grown over the past ten years, and although 2007 saw a reduction in annual production it is predicted to increase again in 2008 to about 22517t (Fig. 2.5). Currently the aquaculture industry provides approximately 550 full time directly employed posts, mainly in marine salmon farming. Related employment is found in processing, marketing and distribution of fish and is approximated at 200 jobs (www.aquaculture.org.uk). The industry took a recent blow with the announcement of the closure of the Lighthouse Caledonia fish processing plant based in Stornoway at the end of 2008 due to bankruptcy (BBC News 27/11/08).

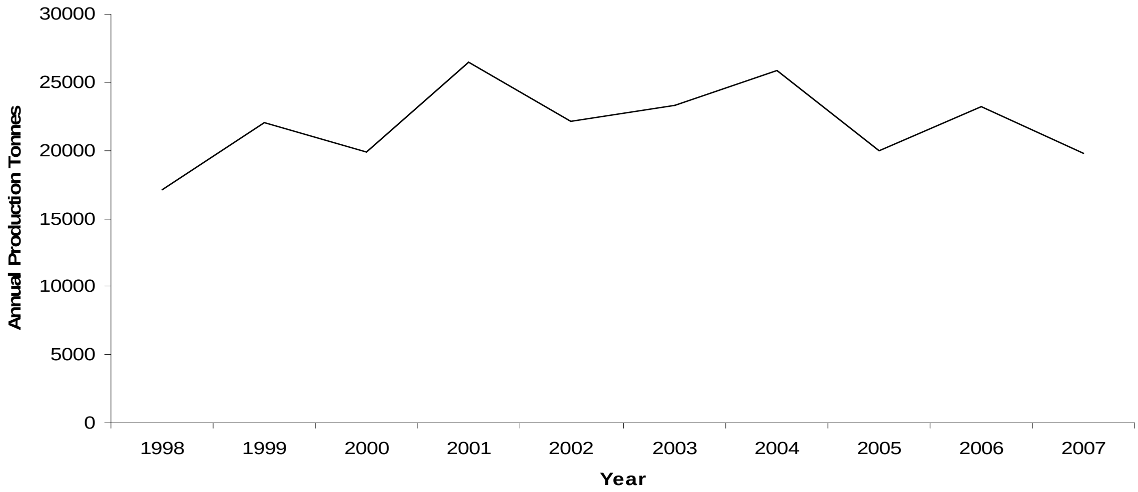

Fig. 2.5: Annual Aquaculture Production for the Western Isles. (FRS, 2008).

2.3 Western Isles Aquaculture Database

The challenges faced for spatial data processing and modelling procedures for the study required a GIS system that has strong modelling capacitlities and is relatively inexpensive. The chosen system was IDRISI Andes (Clark Labs) which is primarily a raster-based GIS software suite ideally suited for the objectives of this study. IDRISI can also incorporate vector data into analyses and cartographic operations and interconversion of formats is relatively straightforward. IDRISI can facilitate a range of data preparation operations, remote sensing, image enhancement and classification, database query and advanced spatial modeling. IDRISI Andes is specifically aimed at environmental monitoring and natural resource management and has a suite of advanced tools for such projects.

One of the most fundamental aspects of IDRISI, the Macro modeller, is a prime reason for it being chosen as the main software. At a basic level the Macro modeler is a graphical environment that allows construction of the multi-step analyses in an open, transparent and easily editable manner. Depending on the required decision process, the macro models developed can be highly complex or very simple and a range of expertise can be brought to bear in developing the rules for these models. The sub-models and final models used are designed in such a way that they can be replicated by a variety of stakeholders, agencies and policy makers.

Behind all of the most effective GIS studies is a highly organized database which is capable of informing and clarifying management decisions. Using data from the spatial database, a hierarchical system of simple mathematical or logical steps can be assembled within the GIS environment. This simple, deconstructed GIS modelling approach has been developed over a long period by the GIS group at the Institute of Aquaculture (Aguilar-Manjarrez, 1992; Ross *et al*, 1993; Aguilar-Manjarrex, 1996; Perez *et al* 2003; Salam *et al* 2003; Perez *et al* 2005). A further important tool in model construction is the use of multi-criteria analysis and the pair wise comparison method, otherwise known as the analytical hierarchy process (AHP) originally described by Saaty (1977). This AHP approach has been implemented in several studies (Malczewski, 1999; Zacharias and Roff, 2000: Utne, 2008) and it includes the ability to maximise the benefits of qualitative information and quantitative factors throughout the decision-making process. The AHP permits weighting of the different criteria used and allows these weights to be altered quickly, along with necessary changes in the underlying databases, thereby enabling rapid production of new suitability models. This is beneficial to modelling for the coastal environment as its dynamic nature means that changes are constantly required as new information and data become available.

The majority of the data used for these sub-models was sourced from internet sources while some was purchased from relevant governing agencies. Most data was supplied in varying formats, projections and resolutions all of which needed some manipulation and conversion before incorporation into the database. All data sources were processed in IDRISI to conform to the utm29n projection. Data used for spatial modelling was rasterised to 30m resolution to match baseline LANDSAT ETM+ imagery. LANDSAT ETM+ was chosen as a suitable baseline due to it being publicly available for download for free. Table 2.1 summarises the important initial data used in this study.

Table 2.1: The factors, constraints, sources and additional information on data used in the Western Isles spatial database.

Database Layer	Description	Supplier/Creator	Source resolution & projection
Western Isles Coast line	Vector line	Edina Digimap. (UK Ordnance Survey)	1:50.,000 Lat/long
Island infrastructure (including Roads, houses, forests, freshwater bodies)	Vector line and polygons	Edina Digimap. (UK Ordnance Survey)	1:50.,000 Lat/long
Digital Elevation Model	Vector Contours	Edina Digimap. (UK Ordnance Survey)	1:50.,000 Lat/long
Aquaculture Sites and production data	Data collected by SEPA on recorded/allowed biomass, chemical usage and waste information for all Western Isles Sites. Vector	Raw data supplied by Scottish Environment Protection Agency; converted to point vector files at Stirling University	Point Data Lat/long
Bathymetry	Vector Contours	BGS Digbath250	1:250,000 WGS84
Seabed substrate type	Vector polygons	BGS	1:250,000 WGS84
LANDSAT ETM+ Satellite images	GeoTIFF Raster	Global Land Cover Facility/ GoogleEarth	30m plane
Land use	Vector polygons	Scottish National Heritage	1:25,000 British National Grid
Protected Areas	Vector polygons. Ramsar, SSSI, SAC,SPA, NSA Vector.	Scottish National Heritage	1:25,000 British National Grid
Current Velocity maximum	Data from tidal diamonds supplied from Maptech	MapTech, chart numbers BA14, BA07 supplemented with data collected by Stirling University	Point Data Lat/long
Shipping Lanes	Vector data for all shipping routes for the main ferry company to and from the Western Isles	Caledonian Macbrayne/ Digitized from Admiralty Charts	1:30,000 Lat/Long
Fish Cage Designs	Kames Fish Farm company supplied information on their cage designs	Kames Fish Cages	Design Documentation
Important View points for Western Isles	Vector point data of SNH survey on important view points on the Western Isles	Scottish National Heritage	Lat/long
Presence Range Polygons: Endangered Species	Data on species for each 10km^2 for the Western Isles completely on land and up to 30km offshore.	National Biodiversity Network	Spreadsheet British National Grid

	A sturio: Baltic Sturgeon *M margaritifera:* Freshwater Pearl Mussel *C maximus:* Basking Shark *G morhua:* Atlantic Cod *M aeglefinus:* Haddock *E esculentus:* Sea urchin *L lutra:* Otter *R clavata:* Thornback Skate		
Presence Range Polygons: species sensitive to aquaculture	Data on species for each $10km^2$ for the Western Isles completely on land and up to 30km offshore. *P. calcareum:* Maerl *T. gouldi:* N. Hatchet Shell *L. coralloides:* Maerl *Z. marina:* Common Eel Grass *L. glaciale:* Maerl *O. edulis:* Native Osyter *M. modiolus:* Horse Mussel *A. nodosum:* Knotted Wrack *C. glaucum:* Lagoon Cockle *F. quadrangularis:* Tall Sea Pen *N. mixta:* Gravel Sea Cucumber *N. lapillus:* Dog Whelk	National Biodiversity Network	Spreadsheet British National Grid
Presence Range Polygons: Species Important for the Western Isles	Data on species for each $10km^2$ for the Western Isles completely on land and up to 30km offshore. *S. alpinus*: Arctic Charr *T. luscus*: Bib *S. trutta*: Brown Sea Trout *P. vitulina*: Common Seal *C. caretta*: Loggerhead Turtle *D. coriacea*: Leathery Turtle	National Biodiversity Network	Spreadsheet British National Grid

	M. molva: Ling *S. salar*: Atlantic Salmon *H. grypus*: Grey Seal *P. platessa*: Plaice *P. pollachius*: Pollack *T. minutus*: Poor Cod *P. virens*: Saithe *M. merlangus*: Whiting		
Landscape Character Assessment (LCA)	Vector polygons	Scottish National Heritage	British National Grid
Fetch Layers	Raster	University of Stirling Modelled through dispersion module for all eight directions 0-360	UTM-29N 30m
Seascape Character Assessments	Raster	University of Stirling	UTM-29N 30m
Proportional Viewsheds	Raster	University of Stirling	UTM-29N 30m
Water Colum Layering	Point Vector	University of Stirling/ UKDMAP 1998 supplemented with data collected by Stirling University	UTM-29N 30m
Mean Salinity bottom and surface (Summer)	Point Vector	University of Stirling/UKDMAP 1998 supplemented with data collected by Stirling University	UTM-29N 30m
Mean Temperature bottom and surface (Summer)	Point Vector	University of Stirling/ UKDMAP 1998 supplemented with data collected by Stirling University	UTM-29N 30m
Fish Spawning and Nursery Areas	Vector data on twelve commercially important fish species. *G. Morhua:* Cod *M. aeglefinus:* Haddock *C. harengus harengus:* Herring *M. kitt:* Lemon sole *T. esmarkii:* Nor pout *P. platessa:* Plaice *P. virens:* Saithe *A. marinus:* Sandeel S. *sprattus:* Sprat *M. merlangus:* Whiting *M. poutassou:* Blue whiting *S. japonicus:* Mackeral	Centre for Environment, Fisheries and Aquaculture Science	1:25,000 Lat/long

Table 2.2 Sub-models developed by University of Stirling and implemented for the Western Isles spatial database.

Sub-model	Description	Supplier/Creator	Source resolution & projection
Species sensitive to Aquaculture	Raster	The 11 Presence Range Polygons were modelled through Land changer model to create Habitat Suitability and Species distribution models. All individual layers were then combined through overlay.	UTM-29N 30m
Protected Areas	Raster	Protected Areas vectors converted to raster and combined through overlay.	UTM-29N 30m
Species Important for the Western Isles	Raster	The 14 Presence Range Polygons were modelled through Land changer model to create Habitat Suitability and Species distribution models. All individual layers were then combined through overlay.	UTM-29N 30m
Endangered species	Raster	The 8 Presence Range Polygons were modelled through Land changer model to create Habitat Suitability and Species distribution models. All individual layers were then combined through overlay.	UTM-29N 30m
Commercially important fish spawning and nursery areas	Raster	The 14 vectors presence were converted to raster and combined through overlay.	UTM-29N 30m
Significant Wave Height	Raster	Developed in a macro model representing Army corps calculation.	UTM-29N 30m
Significant Wave Period	Raster	Developed in a macro model representing Army corps calculation.	UTM-29N 30m
Velocity	Raster	Interpolated from point data	UTM-29N 30m
Bathymetry	Raster	Bathymetry vector contours were reprojected and converted to raster	UTM-29N 30m
Seabed substrate type	Raster	Substrate vector polygons were reprojected and converted to raster	UTM-29N 30m
Water Colum Layering	Raster	Point vector file was interpolated to create surface image.	UTM-29N 30m
Mean Salinity bottom and surface (Summer)	Raster	Point vector file was interpolated to create surface image.	UTM-29N 30m
Mean Temperature bottom and surface (Summer)	Raster	Point vector file was interpolated to create surface image.	UTM-29N 30m
Farm site Polygons	Raster	Vector polygon file was	UTM-29N

		rasterized.	30m
Landscape Sensitivity	Raster	Refinement of Landscape character.	UTM-29N 30m
Seascape Sensitivity	Raster	Refinement of Seascape character	UTM-29N 30m
Visual Sensitivity	Raster	Refinement of proportional viewsheds as defined by current policy guidelines.	UTM-29N 30m
Landscape value	Raster	National Scenic Areas of the Western Isles buffered and reclassed	UTM-29N 30m

Table 2.3 Final models developed by University of Stirling from the sub-models for the Western Isles.

Model	Description	Supplier/Creator	Source resolution & projection
Biodiversity Indicators of Sensitivity	Raster	MCE combination of Species Important for the Western Isles sub-model, Protected Areas, Species sensitive to Aquaculture sub-model, Endangered Species sub-model	UTM-29N 30m
Cage site suitability LMS	Raster	Developed in a macro model through MCE combination of sub models, Significant Wave Height, Significant Wave Period, Velocity, Bathymetry and Seabed substrate type.	UTM-29N 30m
Cage site suitability C250	Raster	Developed in a macro model through MCE combination of sub models, Significant Wave Height, Significant Wave Period, Velocity, Bathymetry and Seabed substrate type.	UTM-29N 30m
Cage site suitability C315	Raster	Developed in a macro model through MCE combination of sub models, Significant Wave Height, Significant Wave Period, Velocity, Bathymetry and Seabed substrate type.	UTM-29N 30m
GIS Multi- site particulate dispersion model	Raster	Developed in a macro model through MCE combination of sub models farm site polygons, Bathymetry and Velocity.	UTM-29N 30m

Western Isles Capacity Model	Raster	Developed in a macro model through MCE combination of sub models	UTM-29N 30m
Holistic Model LMS	Raster	MCE combination of Biodiversity Sensitive, Western Isles Capacity Model, Cage site suitability LMS.	UTM-29N 30m
Holistic Model C250	Raster	MCE combination of Biodiversity Sensitive, Western Isles Capacity Model, Cage site suitability C250.	UTM-29N 30m
Holistic Model C315	Raster	MCE combination of Biodiversity Sensitivity, Western Isles Capacity Model, Cage site suitability C315.	UTM-29N 30m

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Chapter 3

A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Optimising site location based on physical environmental parameters and cage engineering design.

Donna-Claire Hunter, Robert G Smith, Trevor C Telfer and Lindsay G Ross.

This chapter describes the application of GIS as an analytical approach for the improvement of aquaculture resource management to identify appropriate site locations on the Western Isles for sustainable development. This has been recognized as an important requisite stage and sets the base line from which the rest of the sub-models in the study will follow.

The body of the text is presented as a publication-ready manuscript. However, an Appendix section has been included at the end of this paper containing additional supporting figures. This information is not in the body of the text as this did not constitute part of the submitted journal article but is necessary for clarity of the thesis.

The main author, D-C Hunter, developed all sub models and final models. The wave climate sub-model was initiated at Stirling by Dr Philip Scott and was continued by Robert G Smith. It has been further corrected and refined by D-C Hunter. Trevor C Telfer and Lindsay G Ross provided supervisory and editorial support throughout the whole study.

This manuscript has been submitted to *Ocean & Coastal Management*, an international journal committed to the study of all aspects of ocean and coastal management.

GIS-based optimisation of site location for marine cage aquaculture based on physical environmental parameters and cage engineering design.

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Abstract

Defining the physical suitability of an area for marine cage fish farming is of great importance as each cage type has its own engineering tolerance levels and is designed to cope with varying levels of weather and hydrographic conditions, water depth, and anchorage stability. This case study based in the Western Isles of Scotland develops GIS-based models to optimize location of marine cages base on physical environmental parameters and cage engineering design. The models indicate that although the Western Isles has a very restricted development potential for cages designed for sheltered environments ($91km^2$), there is a limited availability for development potential for cages designed for semi exposed environments ($1543km^2$). The greatest potential for aquaculture development is for cages designed for exposed environments ($3103km^2$). These spatial tools can be used to evaluate and optimize the location of marine cage systems and can aid decision making in a more coherent manner than is currently implemented, in line with the principles of the EU Blue Book and the Ecosystem Approach to Aquaculture. These analytical tools can be "stand alone" or can be further integrated into comprehensive management and decision support systems The principles of the models developed can also be applied to coastal zones in the whole of Scotland, or elsewhere.

Keywords
GIS modelling, Aquaculture, Site Suitability, Resource Management, Scotland.

3.1 Introduction

Fish farming in the Western Isles of Scotland, has increased considerably over the past ten years and is likely to continue to develop over the next decade. This expansion has attracted attention in terms of the potential impacts on the environment which range from aesthetic impacts to direct impacts of pollution in the environment.

There is scope for industry expansion to deal with increasing consumer demand, creating a climate of employment to ensure long term business opportunities (Macallister Elliot and Partners 1999) and reducing the current dependence on wild stocks (Williams *et al* 2000). This is particularly relevant to the Western Isles. Whitmarsh and Palmieri (2009) implemented a survey-based approach to evaluate public and stakeholder attitudes in Scotland. The survey results for the Western Isles indicated a marked preference in favour of aquaculture expansion. With this clear public and stakeholder support for aquaculture development the Western Isles is an ideal setting to explore GIS tools for aquaculture development. Locations such as the Western Isles with its public and stakeholder support and its vast coastline could offer ample scope for expansion, subject to understanding of impacts and resilience, and could provide excellent locations for organic aquaculture with high welfare standards. Management practices are needed that guarantee the sustainable management of coastal zones (Turner and Bower, 1999).

Current policies for fish cage site selection have been deemed inadequate and lack the strength to support sustainable development of aquaculture (Scottish Parliament 2002a, b). Current polices and regulatory instruments concentrate solely on the carrying capacity for nutrients within management areas and embayments (Gillibrand *et al*, 1997), which is based primarily on hydrodynamic characteristics and subsequent nutrient retention in the area. Little consideration is given to the actual suitability of a given cage structure and its ability to perform well in an area. Many of the criteria under consideration that are required for the Environmental Impact Assessment process are still based on considering fish farms in isolation (Telfer *et al*, 2009).

Defining the physical suitability of an area for fish farming is of great importance as each cage type has its own engineering tolerance levels and is designed to cope with varying levels of weather and hydrographic conditions, water depth, and anchorage stability. Failure of cages with subsequent loss of fish and equipment is both financially difficult for the operator and potentially has environmental implications due to the interactions between escaped and wild fish. Ensuring that cages are sited appropriately for the particular cage system is fundamental for the sustainability of an operation while also maintaining a high level of safety for operators and the environment. Currently the European Union is motivating a change in coastal marine management (Directive 2008/56/EC) and the Food and Aquaculture Organisation of the UN are pushing an initiative of building an Ecosystem Approach to Aquaculture. Both propose the need for establishment of a framework to protect the marine environment, specifically in a spatial manner. These drives for change underline the need for new tools to achieve integrated governance of the coastal zone and GIS tools are ideally suited for this.

For these reasons fish farming needs to adopt a more structured approach to site location to take into account a regional overview of suitable sites and appropriate selection criteria. The most effective means of achieving this is to use a single process capable of incorporating all of the data needed for determination of site suitability. Much of this information is spatial in nature and therefore the most efficient method of manipulation and modelling using this type of data is to use Geographic Information Systems (GIS) software. GIS modelling can take account of a large number of relevant environmental and socio-economic factors in a spatial format (Nath *et al*, 2000), and through a logical combination of sub-models allows integration of sophisticated analytical tools for multi-site aquaculture planning and management into a coastal zone management plan. Integrated Coastal Zone Management aims at developing organised and considered planning for sustainable development in coastal zones (Vallega, 2001). Assessment of cage site suitability using GIS tools has been described for different scenarios by Ross *et al*., (1993) and Perez *et al.*, (2005).

This paper describes the development and use of a GIS based model of cage site suitability which incorporates the important criteria of currents, bathymetry and wave climate and addresses the importance of siting different types of marine cage technologies based on their physical design capabilities.The chosen study area for this research was the Western Isles off the North West coast of Scotland (Fig.3.1). The island group comprises the five main islands of Lewis, Harris, North Uist, Benbecula, South Uist and Barra, which have a combined coastline length of 2,103km, in which there are multiple sites for sea-cage aquaculture of Atlantic salmon set in a large number of locations with different environmental characteristics including open coast, sheltered bays and fjordic systems. The islands have a wide range of physical environmental characteristics ranging from the open exposed Atlantic coast to easterly facing sheltered and shallow bays.

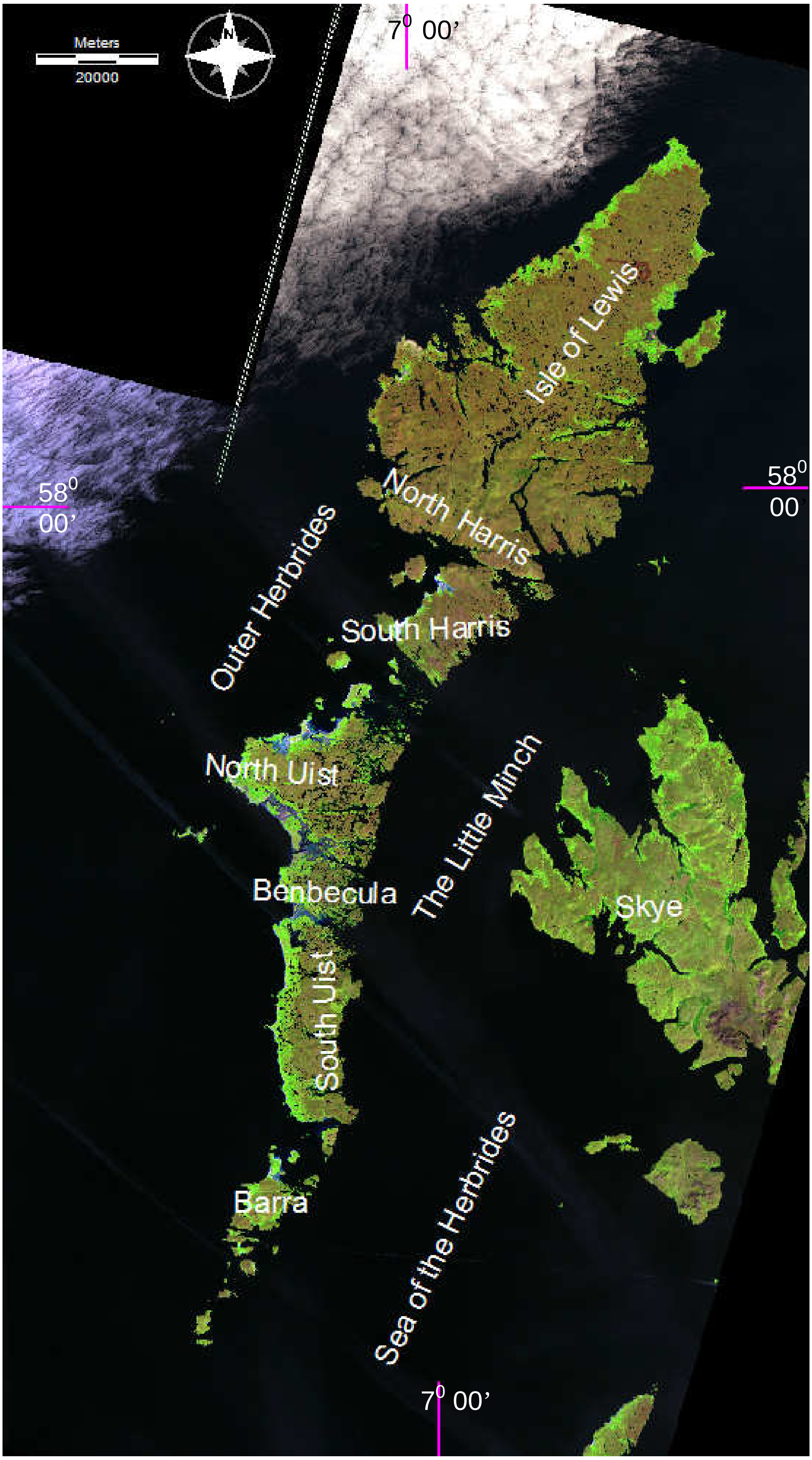

Figure 3.1 The Western Isles off the North West coast of Scotland

3.2 Model components and Development

3.2.1 Cage design parameters

Initial siting assessments can be based upon physical environmental factors related to manufacturers' specific cage designs. Kames Fish Farming Ltd have published guidelines indicating the physical environmental conditions that the designs are able to withstand and these were used in this study. Three cage types were chosen for this study; 1) Large Modular Square cages (LMS) designed for sheltered areas currently used for salmon broodstock and ongrowing, 2) Circular C250 (C250) fish cages designed for ongrowing in fresh or saltwater in semi exposed conditions and currently used in Scotland for trout, salmon and halibut farming, 3) Circular 315 fish cages (C315) used for ongrowing in exposed and offshore conditions. Table 3.1 shows the physical dimensions and maximum threshold limits for each cage type.

Table 3.1 Maximum threshold values for the three differing cages.

Cage Type	**Standard Net Depth (m)**	**Wave Height (m)**	**Currents (kn)**	**Cubic Capacity (m^3)**	**Locations Used**
LMS Designed for sheltered environments	10	1.5	1.4	144 - 625	Greece, Scotland
C250 Designed for Semi exposed Environments	10	3.5	1.6	800 - 700	Greece, Scotland
C315 Designed for Exposed Environments	20	6	1.8	3000 -17000	Chile

3.2.2 Depth

The interpretation of the depth profile for the placement of fish cages can be complex as it is necessary to consider trade-offs allowing sufficient depth below the cages to accommodate the maximum net depth, and also to consider the costs of moorings as depth increases. There are also operational concerns when considering where depth is insufficient and there is likely to be feedback from the waste material built up under the cage (Perez et al, 2003). Water too deep may lead to complications when trying to carry out maintenance of the cages (Gifford *et al*, 2002)

Digital depth vector data was sourced from the British Geographical Survey (DigiBath250, 2005). It was further refined through interpolation to create a raster-based bathymetric map at 30 m pixel resolution and geo-referenced to UTM 29n matching the rest of the database. A full bathymetric surface was interpolated from this data and was then re-classified in terms of suitability for each cage type based on the criteria shown in Table 3.2. KFF supply nets for their LMS and C250 cages with a ten metre depth and recommend a two metre clearance between the bottom of the net and the sea floor. While KFF supply the C315 cages with nets of twenty metres and again recommend a minimum of two metre clearance between the bottom of the net and the sea floor.

Table 3.2 Depth values (metres) re-classified in terms of suitability ranking for each cage design.

Score	**0**	**1**	**2**	**3**	**4**	**5**	**0**
LMS	650 – 50	50 - 40	40 - 30	30 - 20	20 - 18	18 – 12	12-0
C250	650 – 70	70 - 50	50 - 40	40 - 30	30 - 18	18 – 12	12-0
C315	650 – 90	90 - 60	60- 50	50 - 40	40 - 30	30 – 22	22-0

3.2.3 Wave Climate

The wave climate of a sea area and the general sea state at a particular location are critically important when locating cages. The principal elements of a wave climate are the wave height, period parameters, and the wave direction, all of which may contribute to cage damage, stress on structures and an unsafe environment for operators. Dawson *et al* (2001) reported that the Western Isles coastline is relatively insensitive to changes in sea level and instead the frequent occurrence of strong winds and large waves are a more significant issue. The sea state of the Western Isles is also sensitive to the North Atlantic Oscillation. This sensitivity can be seen extending to the more sheltered Sea of the Hebrides.

The height of wind generated waves is a function of wind speed, fetch length and water depth. Water depth affects wave generation where wave heights will be smaller and wave periods shorter in transitional or shallower water. The height of wind generated waves may also be fetch-limited or duration limited. Selection of an appropriate wave climate model thus requires consideration of depth, wind direction, wind speed and fetch length. Scott (2003) successfully used equations developed by the US Army Corps of Engineers

Shore Protection Manual (1984) within a GIS framework to predict the maximum height of waves for aquaculture developments in Sepetiba bay, Brazil. This was further developed by Smith (2005).

For the Western Isles, the updated equations provided by the US Army Corps of Engineers Coastal Engineering Manual (2002) were used to develop a wave climate model. It was necessary to implement four macro models to represent the wave climate. Macros were designed for shallow water (<90m) with one representing wave period and another wave height. Two further macro model calculations for deep water (>90m) representing the wave period and wave height were used. The overall aim was to integrate bathymetry, wind speed and wind fetch data, a significant wave height H_{mo} submodel[1] and a significant wave period T_m submodel[2] into a coastal zone management model. This can then contribute to site suitability assessment for aquaculture projects.

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Wind

Data on wind was supplied in Excel format from the UK Meteorological Office. This data was collected from seven weather collection stations based throughout the Western Isles. For incorporation in the macro model the initial data was refined in two ways and expressed in terms of (a) wind stress factor (U_a) and (b) U^2_a wind^2 stress factor, both in m/s. The deep water calculations for significant wave high and significant wave period implement both wind stress factors while the shallow water calculations for significant wave height and significant wave period only implement wind^2 stress factor (b), where:

$U_a = 0.71\ U^{1.23}$ [1]

$U^2_a = 0.71\ U^{2\ 1.23}$ [2]

Wind directions included in the calculations were 45, 90, 135, 180, 225, 275 and 360 degrees (True North).

Fetch

A fetch layer was created in IDRISI using the method developed by Scott (2003). Fetch can be simply defined as ‘the extent of open water across which the wind blows’ (Bascom, 1964); a larger fetch therefore has a greater wave generating potential as there is more opportunity to absorb energy from the wind (US Army Corps of Engineers, 1984). The Western Isles has a very exposed west coast facing the North Atlantic. The east coast

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1 Significant Wave Height, this is the average of the highest one third of all waves in a time series
2 Significant Wave Period, the average period of the one third highest waves in a wave record.

appears to be more sheltered with the middle of the archipelago being approximately 40km from the Isle of Skye.

Due to the large number of model outputs required a multi-step macro model was developed that allowed a quicker output generation rate once the initial process had been established. (Appendix: Fig. A1)

Wave Climate: Shallow water significant wave height, H_{mo}.

As with the fetch layer; a macro model was developed (Appendix: Fig. A2) to implement the significant wave height equation (Equn 3) used by US Army Corps of Engineers (1984, 2002) and Scott (2003). Once implemented, the wave layer outputs for each direction could be generated, only requiring updates of wind speed and fetch data layers and the final output layer name for each run.

$$H_{mo} = U_a^2 \times 0.28.3 \tanh\left(0.530\left(\frac{9.8D}{U_a^2}\right)^{-0.75}\right)\tanh\left\{\frac{0.00565\left(\frac{9.8F}{U_a^2}\right)^{0.5}}{\tanh\left(0.530\left(\frac{9.8D}{U_a^2}\right)^{-0.75}\right)}\right\} \quad ...(3)$$

Where: $U^2{}_a$ = wind^2 stress factor (m/s)

U_a = wind stress factor (m/s)

D = depth (m)

F = fetch (m)

Finally, the eight wave climate direction layers were combined using the OVERLAY ‘maximum’ function to produce the significant shallow water wave height model for the Western Isles. This represents the average of the highest third of all waves in a time series as defined in (US Army Corps of Engineers, 1984).

Wave Climate: Deep water significant wave height, H_{mo}.

Using the same wind stress factors and fetch layers created initially for shallow water, a further macro was developed (Eqn 4) to implement the deep water equation used by US Army Corps of Engineers (1984) to represent the significant wave H_{mo} (Appendix: Fig. A3).

$$H_{mo} = \frac{U_a^2 \times 0.0016\left(\frac{9.8F}{U_a^2}\right)^{-0.5}}{9.8} \qquad \text{………………. (4)}$$

This calculation assumes that winds have blown constantly and for long enough for wave heights at the end of the fetch to reach equilibrium. Although this will not always be the case, it is the most likely scenario occurring in the study area. Finally, the eight wave climate direction layers were combined using the OVERLAY 'maximum' function to produce the deep water maximum sustained significant deep water wave height model for the Western Isles.

Overall H_{mo} Wave height Submodel

The shallow water and deep water significant wave height models were finally combined by maximum overlay. The final submodel for H_{mo} wave height was reclassified against the threshold values for each of the three cages (Table 3.3)

Table 3.3 H_{mo} wave height (metres) re-classified in terms of suitability ranking for each cage design.

Score	**0**	**1**	**2**	**3**	**4**
LMS	>1.5	1.25 - 1.5	1 - 1.25	0.5 - 1	0 - 0.5
C250	>3.5	2.75 - 3.5	2 - 2.75	1.75 - 2	0 - 1.75
C315	>6	4.5 - 6	3.5 - 4.5	3 - 3.5	0 - 3

Wave Climate: Shallow water wave period, T_m.

Wave period is defined as "the time taken for a wave crest to travel a distance equal to one wave length." (Beveridge, 2005). Inshore sites generally experience wave periods that are typically shorter than offshore sites at around 2.5 - 6secs. Wave periods can cause structural failure through metal fatigue, the welded components of a cage structure being the most vulnerable to this type of environmental impact (Wolfram and Feld, 1996). The significant wave period can be described as the average period of the highest one third of all waves in a series, and can be calculated using equations from the US Army Corps of Engineers, (1984). This was implemented in two macro models, one for shallow water of less than 90m depth (Appendix: Fig A4) and another deeper water over 90m depth (Appendix: Fig. A5).

$$T_m = \frac{U_a \times 7.54 \tanh\left(0.833\left(\frac{9.8D}{U_a^2}\right)^{3/8}\right) \tanh\left\{\frac{0.0379\left(\frac{9.8F}{U_a^2}\right)^{1/3}}{\tanh\left(0.833\left(\frac{9.8D}{U_a^2}\right)^{3/8}\right)}\right\}}{9.8} \qquad \text{………. (5)}$$

where: U^2_a = wind^2 stress factor (m/s)

U_a = wind stress factor (m/s)

D = depth (m)

F = fetch (m)

It should be noted that when the OVERLAY division function is used, as in this macro model, zero values will not compute and the macro model will fail, consequently all zero values were given a very small positive or negative value before use in the macro model.

Finally, the eight wave climate direction layers were combined using the OVERLAY 'maximum' function to produce the shallow water wave period model for the Western Isles

Wave Climate: Deep water wave period, T_m.

The wind stress factors and fetch layers created initially were used in a further macro model based on Eqn 6 (US Army Corp of Engineers, 1984), to represent the wave T_m deep water.

$$T_m = \frac{U_a \times 0.2857\left(\frac{9.8F}{U_a^2}\right)^{1/3}}{9.8} \qquad \text{…..… (6)}$$

Overall Wave period Submodel.

The shallow and deep water wave period models were finally combined using overlay. The final submodels for T_m wave period were reclassified against the threshold values for each of the three cages (Table 3.4).

Table 3.4 T_m wave period (seconds) re-classified in terms of suitability ranking for each cage design.

Score	0	1	2	3	4
LMS/C250 /C315	0	1 - 2	0.75 - 1	0.5 - 0.75	0 -0.5

3.2.4 Maximum Current Velocity Sub model

The effect of current velocity cannot be underestimated. It not only affects the physical structure of the cages through torsional forces on the netting, fatigue and fracture on welding points but also affects fish production and behaviour through deformation of nets, reduced oxygen supply or waste clearance and even excessively forced swimming. Data availability on maximum current velocity was sparse and therefore point data from numerous sources was collected and combined in a point vector file. The information was further refined using triangular network surface interpolation procedures to create a raster surface image. This created a maximum current velocity image which was reclassified in terms of the threshold values shown in Table 3.5. Ideally, a minimum current velocity sub model would have been developed, but the scarcity of such data made this difficult for such a large study area.

Table 3.5 Current velocity (knots) re-classified in terms of suitability ranking for each cage design

Score	0	1	2	3	4
LMS	>1.4	1.2 - 1.4	1.1 - 1.2	1 - 1.1	0 - 1
C250	>1.6	1.4 - 1.6	1.2 - 1.4	1 - 1.2	0 - 1
C315	>1.8	1.6 - 1.8	1.3 - 1.6	1 - 1.3	0 - 1

3.2.5 Substrate

Substrate at sites can be an extremely influential factor. Cost of moorings at rocky sites may be problematic and expensive, although this can also be a sign of good current scour thereby reducing the risks of waste accumulation (Beveridge, 2005). Similar to those issues surrounding depth, interpretation of this criterion becomes a “trade off” issue. Data was collected from various sources including British Geological Survey (BGS), United Kingdom Digital Marine Atlas and Environmental Impact Assessment studies carried out by the Environment Services group (Institute of Aquaculture). This data was digitized and reclassified using a five category sediment type profile based on those designed by BGS and focusing on European Nature Information System habitat classifications. This classification uses the common Folk (1954) triangle, which merges them into four major categories (Appendix: Fig. A6). This was further adapted for this study by addition of a fifth substrate type, Rock. The substrate types were finally reclassified in terms of suitability for the three target cage types, as shown in Table 3.6.

Table 3.6 Substrates re-classified in terms of suitability ranking for each cage design

Score	**0**	**1**	**2**	**3**	**4**
LMS/C250 /C315	0	4 - 5	3 - 4	1 – 2	2 - 3

3.3 Overall Model Structure

Following development of the components of the spatial database of relevant environmental variable, all data were converted to the international UTM 29n geo-referencing system within a raster spatial database at 30m resolution. Cage suitability models were then created for each of the three cage types employing the GIS software IDRISI^{TM} Andes (Clarks Labs, 2006). The principal sub-units of this model were, significant wave height, significant wave period, bathymetry, current velocity and sediment type and these physical environmental factors were reclassified in terms of suitability based on the cage physical environmental limits as defined by the manufacturer (Table 3.1) on a 1 to 10 scale, where 1 is least suitable and 10 most suitable. The reclassified factors were then weighted in order of importance before final combination using a Multi-Criteria Evaluation approach within the GIS framework (Fig. 3.2). Multi-criteria decision making is formulated using the Analytical Hierarchy Process technique (Saaty, 1980) which, as previously shown for cage aquaculture by Perez *et al* 2005, provides a framework to represent the decision groups and which allows incorporation of disparate variables into a single model. The AHP approach has many advantages including its simplicity and flexibility and as a result has been highly successful in its application (Ramanthan, 2001). This type of modelling approach allows results to be quantitatively expressed and strengthens the process of aquaculture planning and location guidelines.

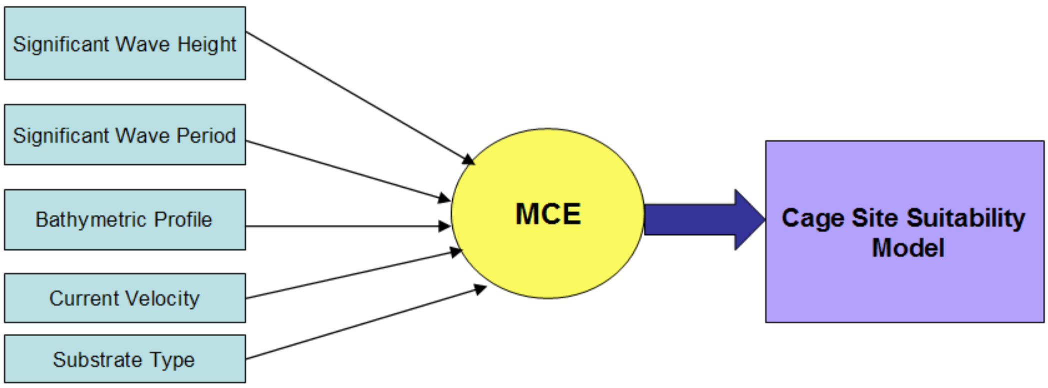

Fig. 3.2 Simplified version of Cage Site Suitability model for the Western Isles using the five predefined physical parameters.

3.4 Results

3.4.1 Depth

The bathymetric sub-model shows a depth profile that gradually deepens on the Western coast in comparison to the Eastern coast which shows a sharp depth increase (Fig. 3.3). Farms established along the eastern coast can be in deep water while still relatively close inshore.

3.4.2 Significant wave height (H_{mo})Sub-model.

The overall sub model for significant wave height indicates that the Sea of the Hebrides and the North of Lewis are highly exposed while South Harris and the western coasts of the Southern Isles are much less exposed to significant wave activity (Fig. 3.4). This was partly validated from the results of a previous study (Baxter *et al*, 2008) in which a significant wave height model was created for the whole of Scotland based on a 2nd generation spectral scheme (Golding, 1983) which combines observational data from satellite, ship and meteorological buoy networks at a spatial scale of 12km. Their results highlighted greater exposure in the same areas as those identified here.

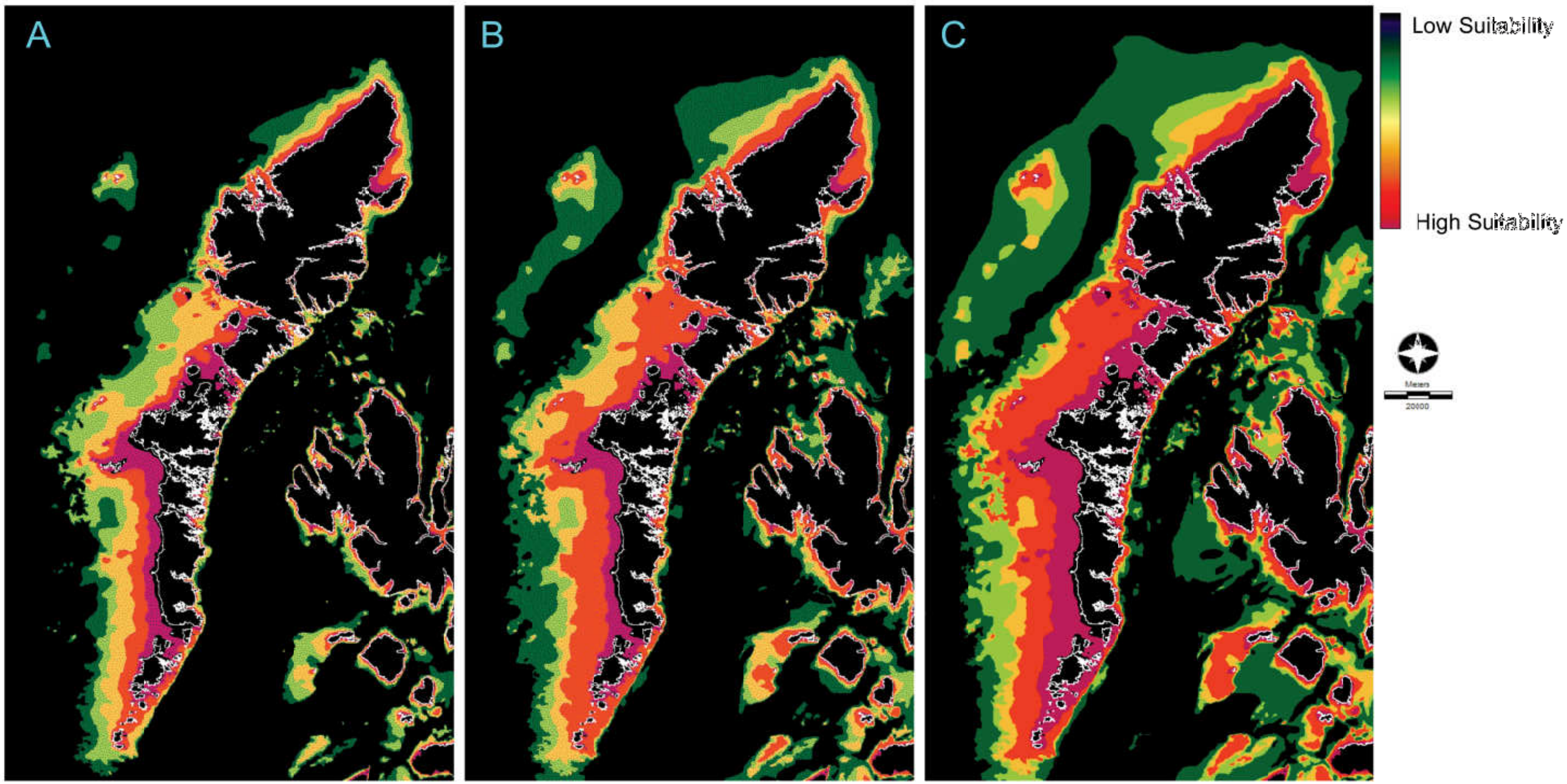

Fig 3.3: Site selection for all three cage types based on bathymetry. A = LMS (for sheltered environments), B = C250 (for semi-exposed environments) and C = C315 (for exposed environments).

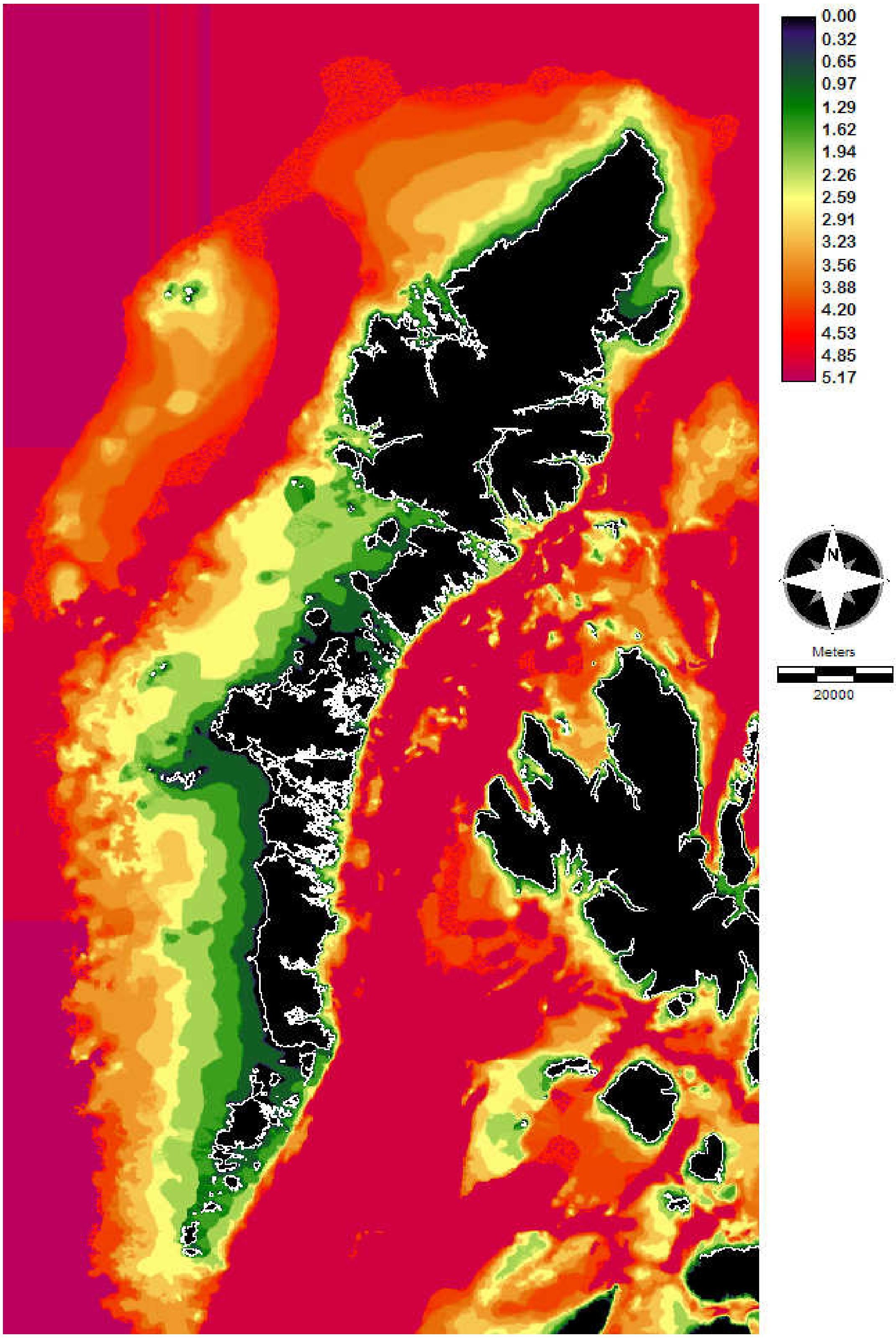

Fig.3.4 Distribution of shallow water significant wave height (H_{mo}) for the Western Isles. Wave heights are in metres.

3.4.3 Overall wave period Sub-model

The significant wave period is considerably longer in duration in the Minches and along the eastern coastal line of the islands where it is in the range of five to eight seconds (Fig 3.5). By contrast, on the western side of the coastline the wave period is significantly shorter in the range of one to three seconds.

3.4.5 Maximum Current Velocity Sub-model

The model results indicated that most of the coastline of the islands and the Little Minch experience higher current velocities in the range of 1kns to 2kns (0.5 to 1 $m.^{s-1}$), compared to the North part of Lewis which has a lower current velocity of between 0.65kns to 1kns (0.3 to 0.5 $m.^{s-1}$) (Fig. 3.6). Overall the distribution of maximum current velocity is indicative of a high flow rate which is highly suitable for aquaculture production. However, it should be noted that this model is based on sparse data points and could be subject to improvement when more data becomes available.

3.4.6 Substrate

Substrate type varies around the islands in a complex manner (Fig. 3.7). The western coastline of the southern isles is dominated by a rocky bottom, while the eastern coastline of the southern isles is dominated by sand and muddy sand. Moving north to the Isle of Lewis, Loch Roag it can be seen that it is dominated by sand and muddy sand while the eastern coastline of Lewis varies from sand and muddy sand to mixed sediments.

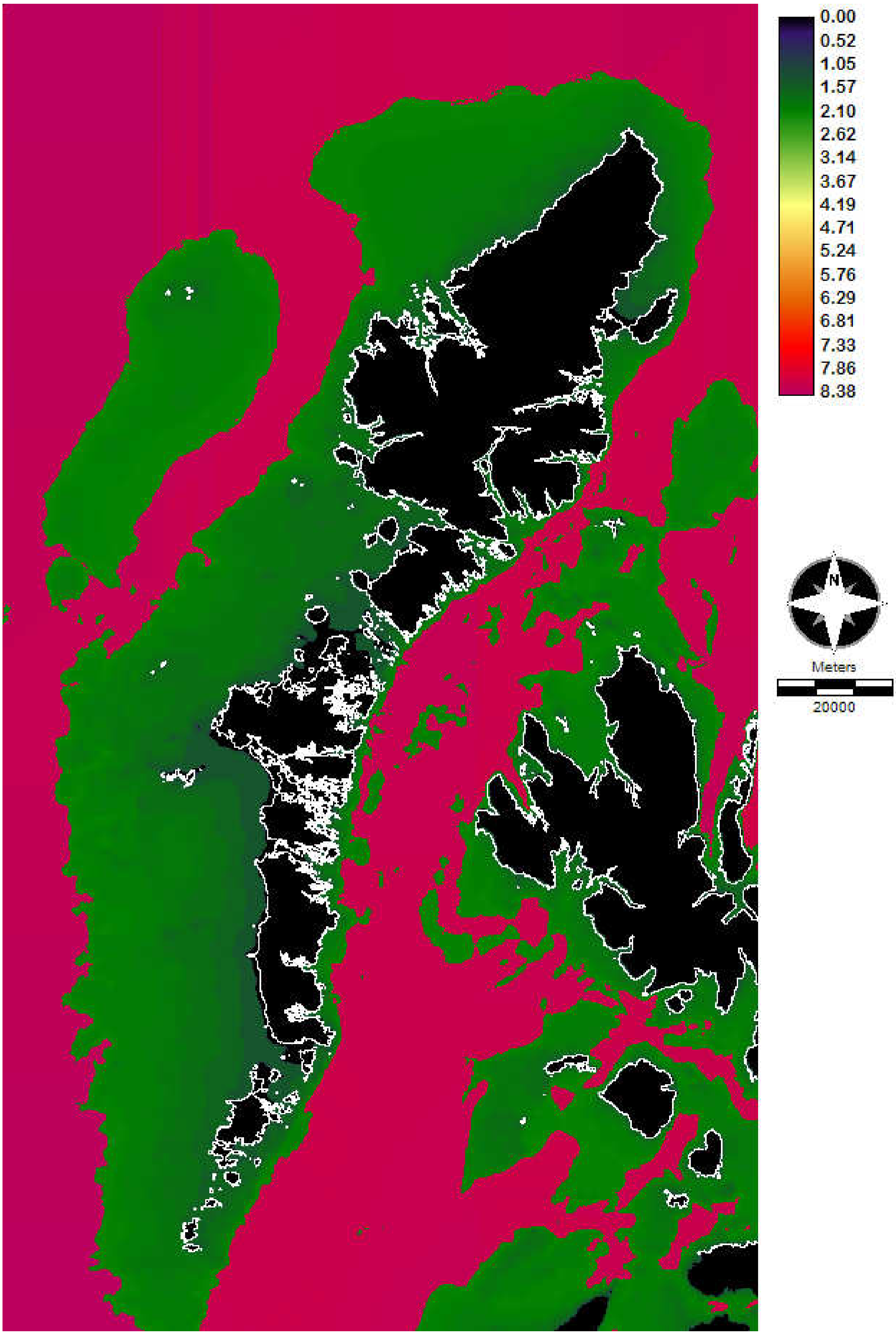

Fig.3.5 Distribution of significant wave period (T_m) for the Western Isles. Wave period is given in seconds.

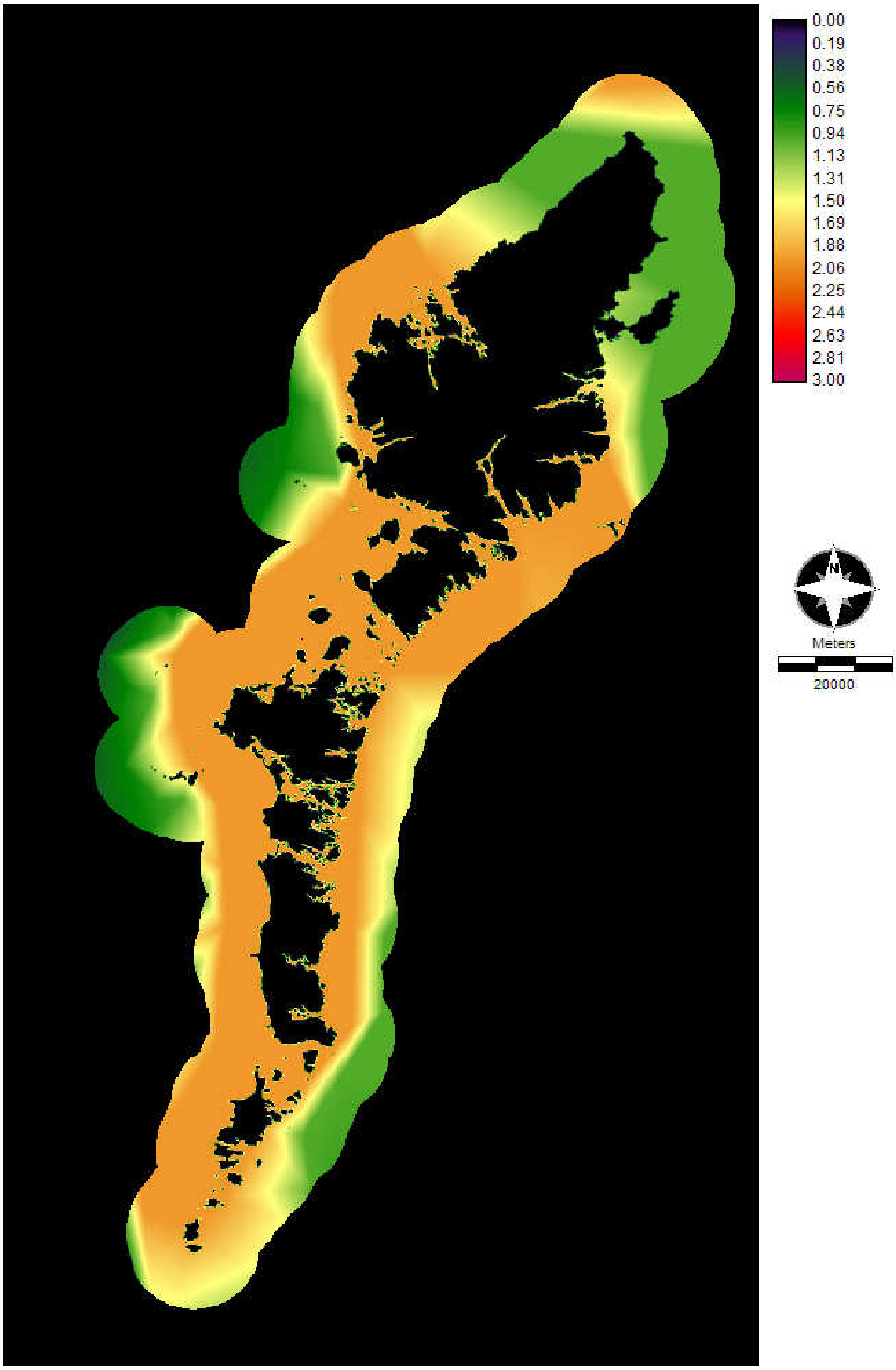

Fig.3.6 Distribution of maximum current velocity around the Western Isles, Scotland. Current velocity is in knots.

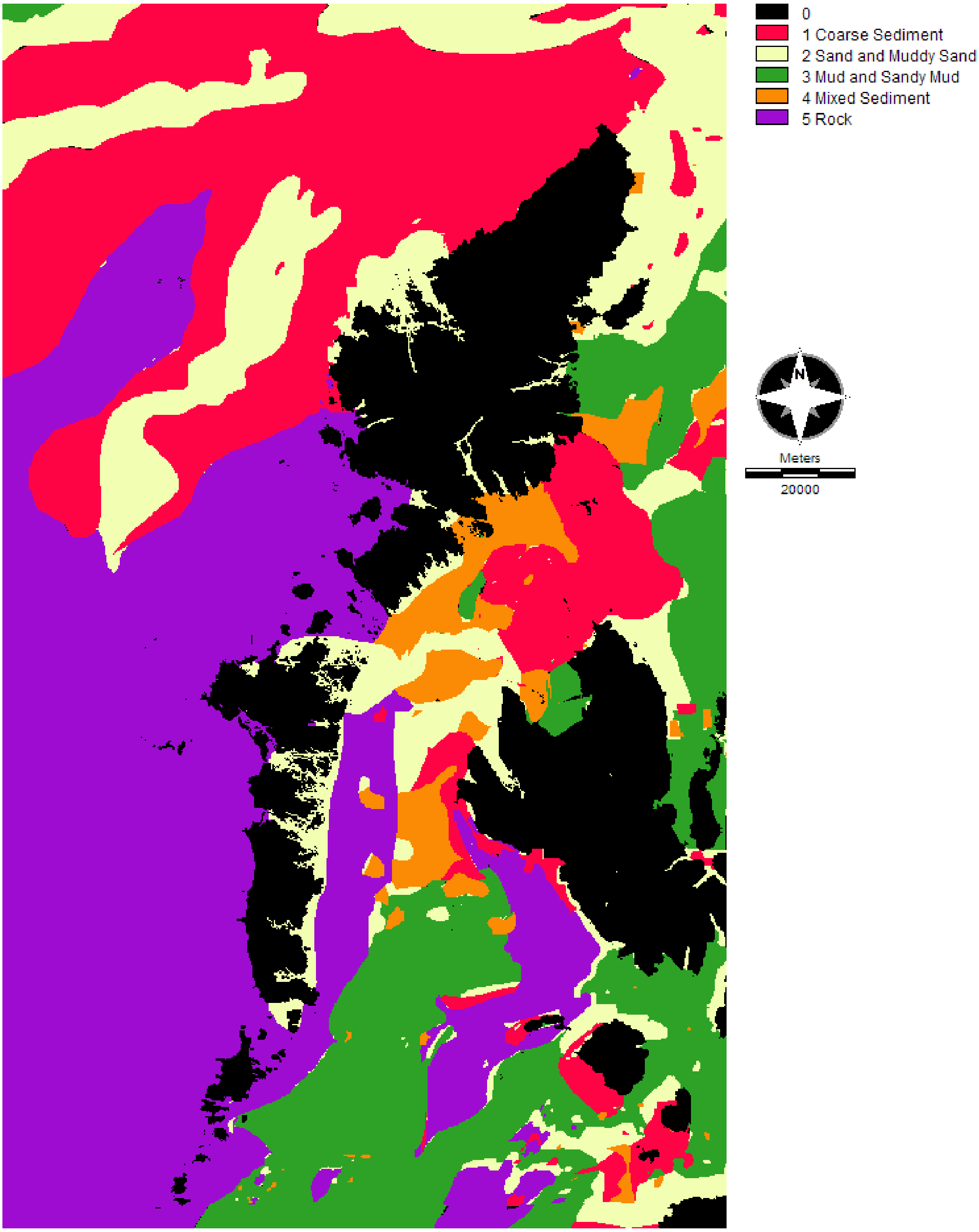

Fig 3.7 Distribution of marine substrate type around the Western Isles, Scotland.

3.5 Cage Site Suitability Models

The final cage site suitability models were created using a weighted MCE process (Kapetsky and Aguilar-Manjarrez, 2007 and Store, 2009), in which each initial submodel is weighted to indicate relative importance. Whilst such weighting is often determined subjectively by 'experts' in regards to aquaculture, Aguilar-Manjarrez, 1996 noted that groups of experts, even from similar backgrounds, may consider the ranking of importance in quite different manners. Another consequence in relation to the weight factors is that experts with different backgrounds and agendas may have differing views on the weights and this can also result in a range of outcomes (Nath *et al*, 2000). To accommodate this, a range of ten aquaculture experts from the Institute of Aquaculture (Stirling University) were asked to rank the selected physical factors in order of importance. The resulting weights calculated from these rankings can been seen in Table 3.7.

Table 3.7 Weightings for each of the five initial criterions for the final Site Suitability Model.

Factor	Weighting
Significant Wave Height	0.4897
Significant Wave Period	0.2644
Depth	0.1264
Substrate	0.0754
Velocity	0.0752

The models for the KFF LMS sheltered inshore cages (Fig 3.8) show that ideal locations are restricted to inshore sea lochs covering an area of approximately 91km^2 (10% of the study area). The most appropriate locations for this type of cage are in the sheltered areas of Benbecula (A), Loch Leurbost, Loch Erisort (B) and several areas of South Uist (C). Siting of this cage type in Loch Roag (D) is limited by the physical environment of wave climate except within the innermost parts. By contrast, the models for the less sheltered KFF C250 cages show that approximately 1543km^2 (37% of the study area) of coastal waters are favourable (Fig. 3.9). Most of these areas can be found in the sea lochs as well as in some open coastal areas. The northern coast line of Lewis (A and B), the eastern coastline of North Uist and Benbecula (E) show favourable conditions along with some parts of West Loch Tarbert (C). Greater areas of Loch Roag are suitable for this cage type than for the sheltered area cages. The KFF C315 exposed cage type (Fig. 3.10) has the greatest number of suitable areas of the three modelled at approximately 3103km^2 (65% of the study area). Almost the entirety is located off shore as the design of the cages uses a net with a depth of between 15 and 25m restricting their ability to be placed in shallower seas. Extremely suitability areas for this type of cage can be found off shore of the lower isles (A and B) while outermost parts of the isles sea lochs such as Loch Roag (C), Loch Seaforth and East Loch Tarbert (D) and Loch Skiport (E) are extremely favourable for this cage type.

3.6 Model Validation

To verify the final sub-model suitability outputs, comparisons were made between the predicted suitable areas and those of the existing farm locations. The model for semi exposed cages was explored further as the majority of fish cages in use in the Western Isles are based on this design, although are not necessarily from this manufacturer. Overlaying the locations of present aquaculture farms onto the cage suitability model for semi-exposed cages demonstrates that currently over forty percent of farms are located within areas that are predicted by the model to be suitable for the semi-exposed cage type (Fig. 3.11).

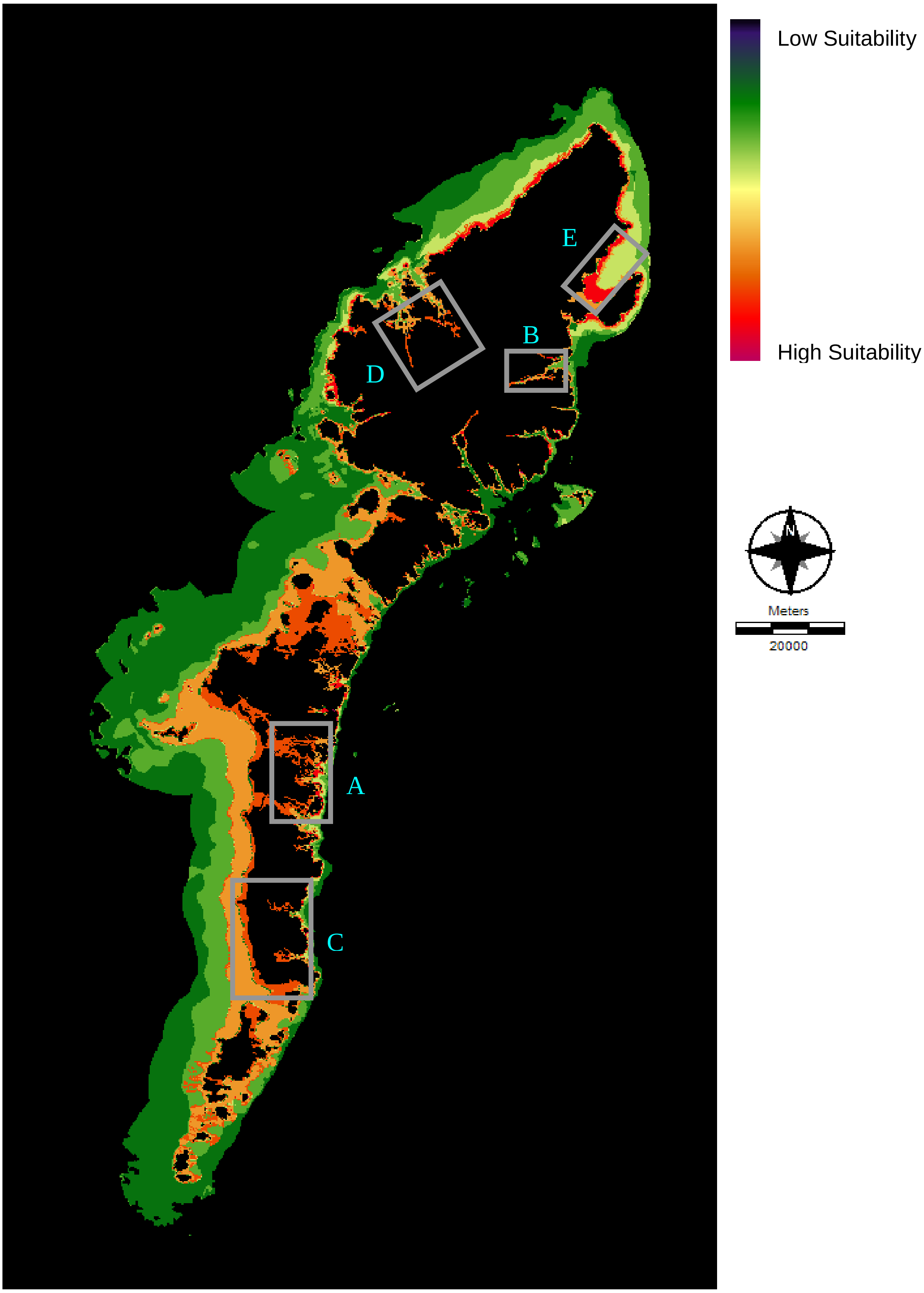

Fig. 3.8 Cage Suitability Model for the KFF Large Modular Square cages designed for sheltered inshore waters.

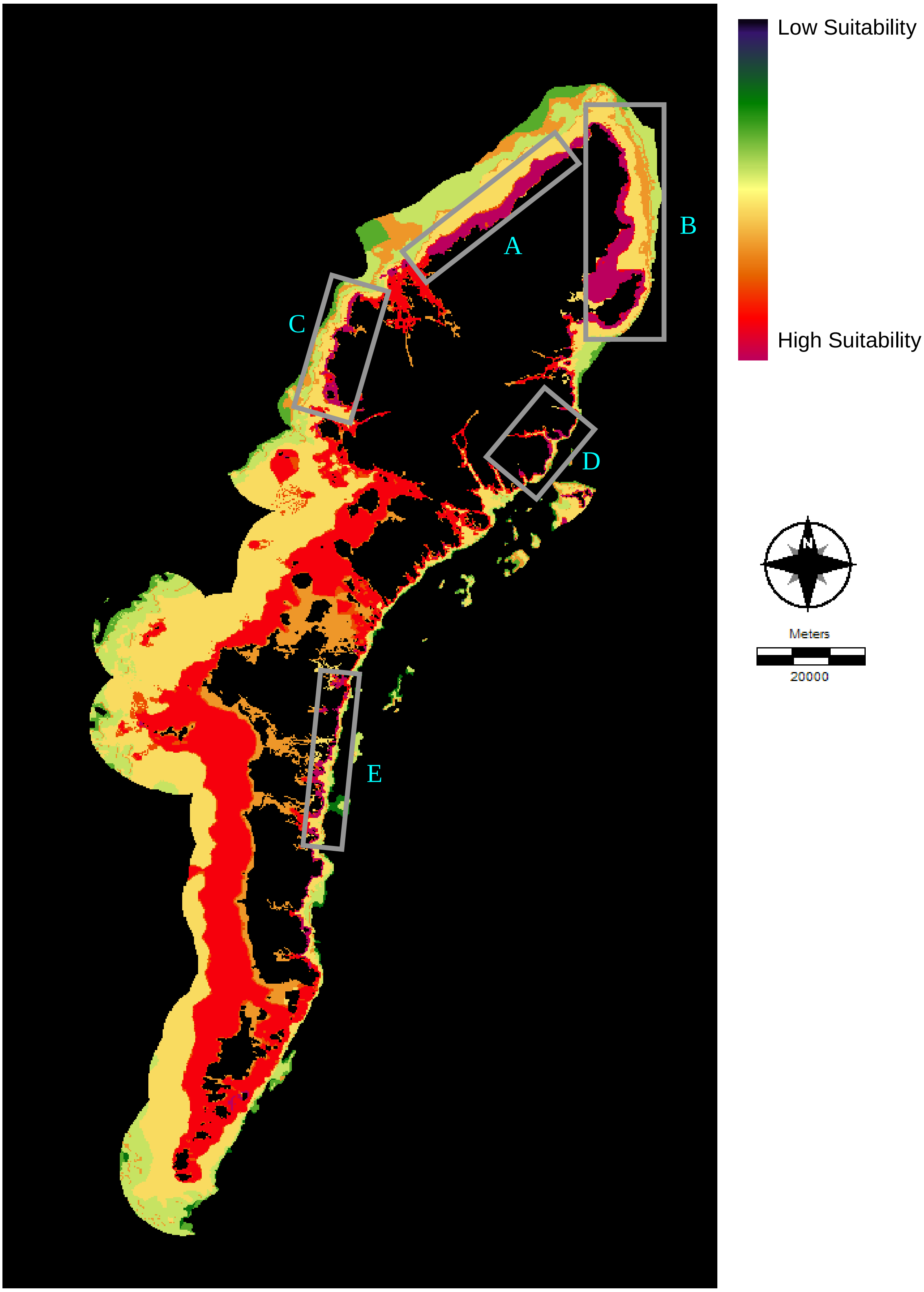

Fig. 3.9 Cage Suitability Model for the KFF Circular 250 cages designed for semi-exposed waters.

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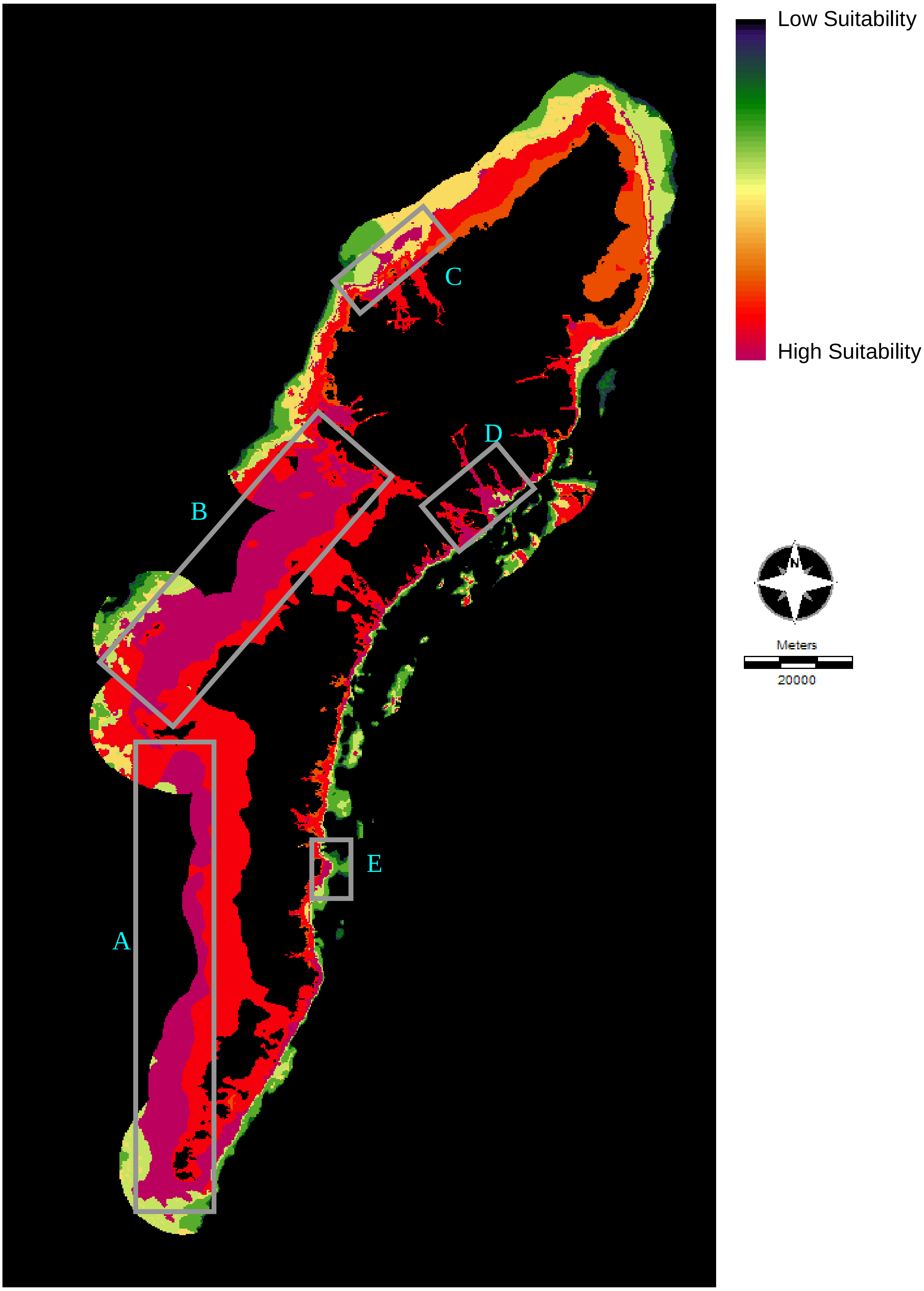

Fig. 3.10 Cage Suitability Model for the KFF Circular 350 cages designed for exposed offshore waters.

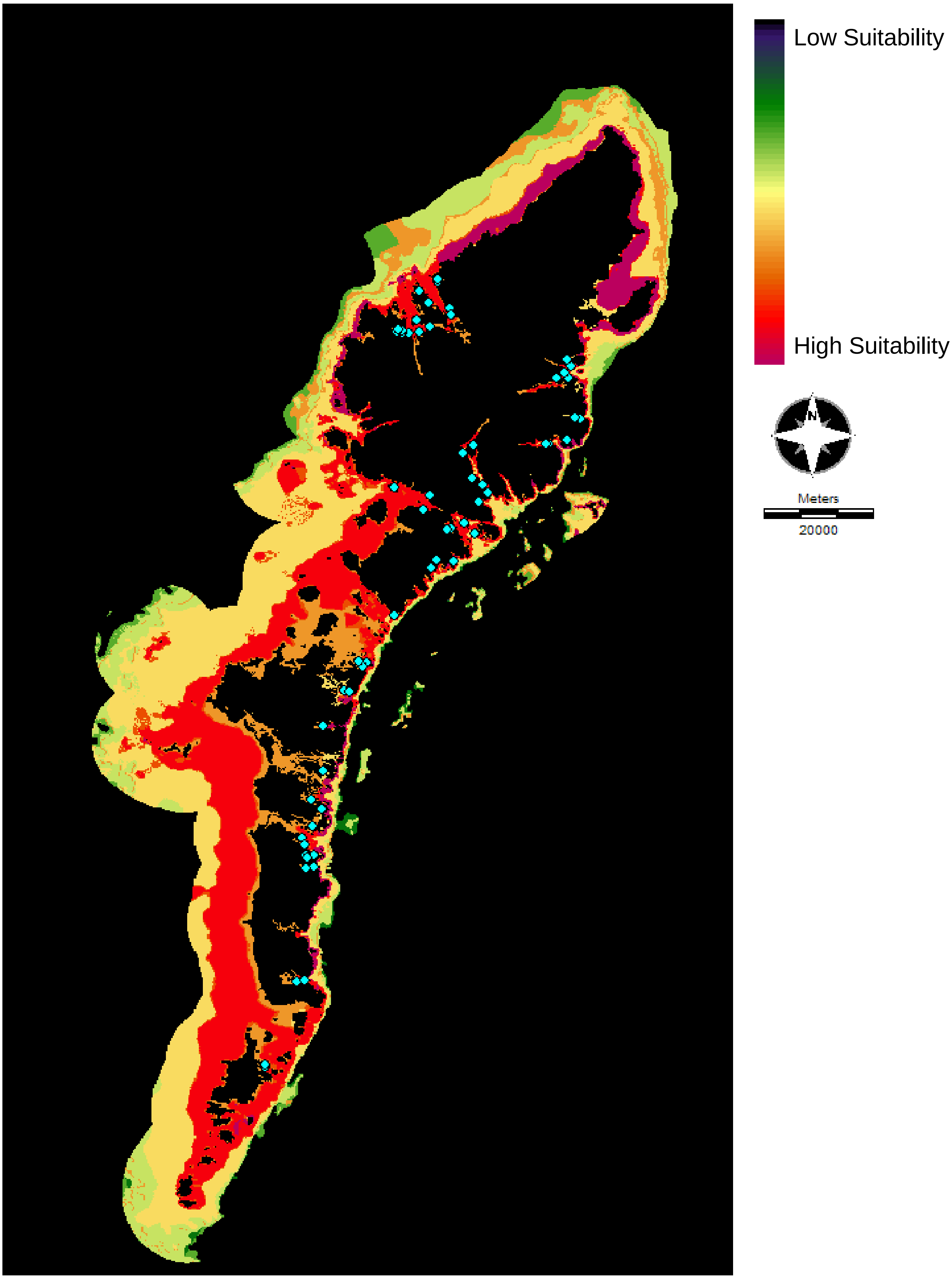

Fig.3.11. Current active fish farm locations in the Western isles (indicated as cyan dots) overlaid on the C250 cage suitability model.

3.7 Discussion

A key issue in any aquaculture operation is appropriate site selection, if the best sites appropriate for different types of cages are not selected, then this can have downstream effects on a farms success, long term sustainability and environmental resilience. Longdil *et al*, (2008) noted that the most suitable and sustainable locations for aquaculture can be identified through targeted data collection programmes and the subsequent implementation of GIS based models, This study presents an application of site suitability modelling for marine cage aquaculture, developed with in a GIS framework. The principal aims were to identify relevant environmental and engineering criteria for cages and to create a robust methodology that is flexible, adaptable and where the resulting outcomes are easily understandable. These are highly important advantages emerging from use of GIS (Rajitha *et al*, 2007).

This study was undertaken specifically to identify suitable sites for three types of cage used for ongrowing in exposed and offshore conditions, in the Western Isles, Scotland. GESAMP (2001) noted that this type of approach is appropriate for the location of aquaculture and is highly suited to maximizing the overall economic return. This is not at the expense of the environment and this approach ensures that potential conflicts between aquaculture and other resource use is predicted and understood. The model developed here is relatively easy to implement. The initial data development in certain areas e.g. wave climate can be problematic due to the lack of full data sets for a given study area. However, with the drive to approach marine planning in a spatial manner (Kapetsky and Aguilar-Manjarrez, 2007) these problems are likely to become much less of a hindrance as digital data sources improve and with the wider adoption of this type of management framework. The resolution finally implemented of 30metres is appropriate for the production system type and the size of the study area. Although there may be value in using a finer spatial resolution of, say, 10m (Perez *et al*, 2003), the use of pansharpened LANDSAT ETM+ baseline imagery at 14.25 metres resolution is more than adequate for most purposes. Interestingly, many of the wide field models being created for the Scottish marine environment have a much coarser resolution of twelve kilometres (Baxter *et al* 2008).

The recent publication by Baxter *et al* 2008 “Scotland’s Seas: Towards Understanding their State” aims at establishing a baseline against which future marine and coastal policy can be measured. The main report is due for publication in 2010. This sets out a comprehensive baseline of data in a spatial format, some of which are used in the present study. However, all data layers used in this model required manipulation, reclassification, and georeferencing and development at a resolution to match the whole database. This comparability and consistency in each layer is necessary to enable algebraic manipulation and Multicriteria Evaluation The study presented in this paper shows how these models can be implemented in a framework for future marine and coastal policy. This is not a new concept. Aguilar-Manjarrez and Ross (1995) identified the positive benefits of the spatial format as an analytical and predictive tool for aquaculture, while Frankic, (1998) highlights the importance of developing an analytical framework that can incorporate spatial and temporal dimensions. The Crown Estate also envisaged the need to approach the governance of the sensitive marine environment in a proactive management stance and recently introduced its Marine Resource System (MaRS). MaRS is a GIS decision-support tool which explores the identification of potential areas for sectoral development and has been successfully applied to wind farm development off shore (http://www.thecrownestate.co.uk/mars). The present study extends this further by showing how frameworks and polices for aquaculture in Scotland can be applied to the process.

Some of the model components used are in themselves highly complex and can be independent tools. Wave climates are one example and their impacts on the environment have been explored in numerous ways. The relationships between wave exposure and species distribution or wave climate and coastal erosion have been explored (Bekkby *et al* 2008; D'iorio, 2003) and models have been designed solely to explore wave climate scenarios, (SCAPEGIS, 2005) Determining the likely wave climate risk of an area is a critical factor for the support of coastal zone management for development of any activity. A recent pilot study on aquaculture site optimization for Loch Roag highlighted that "adequate specification and siting of salmon farm installations in respect of hydrological in particular wave climate" should be taken into account (Tyrer and Bass, 2005). It is clear that this one sub model achieves this objective. Although wave period has always been considered an important factor it is very rarely included in an EIA. The model developed here is a significant step forward into bringing this important criterion into consideration. Whilst there is a well established understanding of how wave height will impact aquaculture structures (Panchang *et al*, 2008) other wave climate factors such as wave period are much less understood and require further investigation.

Current velocity proved extremely problematic in development as there was very little data available and it was spread thinly throughout the study area and as a consequence, the results may not be as robust as others. However, this factor is very important as a range of other factors from safety to fish production and the structural integrity of the cage framework and nets can be affected if cages are sited in appropriate current velocities (Beveridge, 2005). A further beneficial development would have been the incorporation of minimum current velocity, although such data is sparse and this would require considerable field work.

Substrate is an important component of the model and the potential influence the type of substrate will have on aquaculture structures is well documented (Beveridge, 2005). This factor has previously been identified as important when considering cage site locations (Halide *et al*, 2009) The varied pattern of substrate through out the islands indicates that this is an important factor that needs to be considered. The type of substrata is an indication of its anchorage stability where softer sediments are less stable and at higher risk of failure in mooring systems. Whereas rocky type sediments will be more stable but the types of moorings required to be used in a harder substrata are more expensive thus both types of substrate will have possible economic implications when considering locations.

This site suitability model, based on physical environment and engineering considerations, forms an important component of a wider set of decision support tools, specifically for marine cage aquaculture in the Western Isles, although the framework can be easily extended to the whole of Scotland, or indeed other parts of the world. There are however numerous important factors to be considered for selecting the optimal location in aquaculture as highlighted by Nath *et al* (2000). Also for optimal site selection location for aquaculture it should not be based on one criterion alone but must consider multiple criteria (Ramesh and Rajkumar, 1996). The factors considered here are relevant to this particular study.

This study has clearly shown that, in this environment, long term operational success is most likely to be achieved by cages designed for exposed locations, whilst cages designed for more sheltered environments have very little scope for further deployment. Cages designed for semi exposed environments are already well utilized and exploited in many areas. The models provide suitability scores for the different cage technologies and these enable environmental managers and regulators to make decisions about siting of cage culture or alternatively to identify other potential locations within a similar locality or management area. This process is in marked contrast to the current EIA process of site selection. It allows a proactive approach to ranking areas and developing options of sites instead of a simple “yes or no” response to single site queries. This type of decision support tool is not only intended as a fixed engine for regulation but is ideally suited for use at the exploratory, pre-development stages. These models support previous research, for example, those suggested in the Loch Roag site optimization plan (Tyer and Bass, 2005) who noted that “the positioning of the cages should be guided by spatial models.” This will enable the correct technology to be used in the most appropriate environments, ensuring long term site viability with minimal costs, a safer working environment and minimizes the potential of production losses.

There are currently a range of means of making decisions in relation to aquaculture sustainability. Some are through GIS, others are non-GIS applications. These aquaculture decision support systems all consider different aspects which are important for the successful operation of aquaculture, such as those for selecting sites (Halide et al, 2009), optimization of production (Ferreira *et al*, 2009), determining waste impacts (Corner *et al*, 2006; Giles et al, 2009), disease monitoring (LI *et al*, 2009) and efficacy evaluation (Mostafa, 2009). Despite the fact that these are all highly important considerations they are highly complex and are not easily considered as a group when making decisions for aquaculture. The underlying major strength of a GIS-based model is a that it can be expanded and built upon and taken further by incorporating other sub models according to the defined issues including aspects of environmental, ecology, economics and support facilities (Riadiarta *et al*, 2008). A sufficiently realistic model, once implemented, calibrated and validated may play a strong role in formulating or adapting a regulatory framework. (Rennie *et al*, 2008)

This study has shown that, with suitable information which is structured in a spatial manner, GIS can be a strong analytical and modelling tool for aquaculture site selection management. Further adaption of GIS frameworks to include other factors for sustainable aquaculture development must be included. These should include, biodiversity (Hunter *et al*, 2007) and environmental impact (Bricker *et al*., 2003; Viaroli *et al*., 2004; Devlin *et al*., 2007) As frameworks and polices are developed and with data becoming increasingly available the effectiveness of such tools and models will increase and can become a major feature in ensuring aquaculture’s sustainable future.

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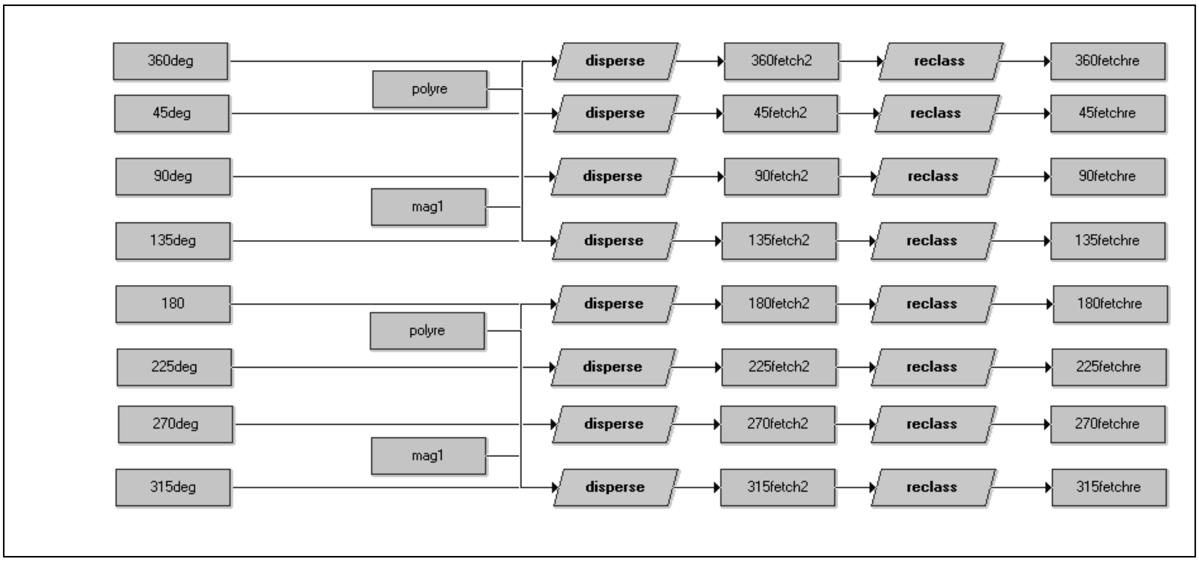
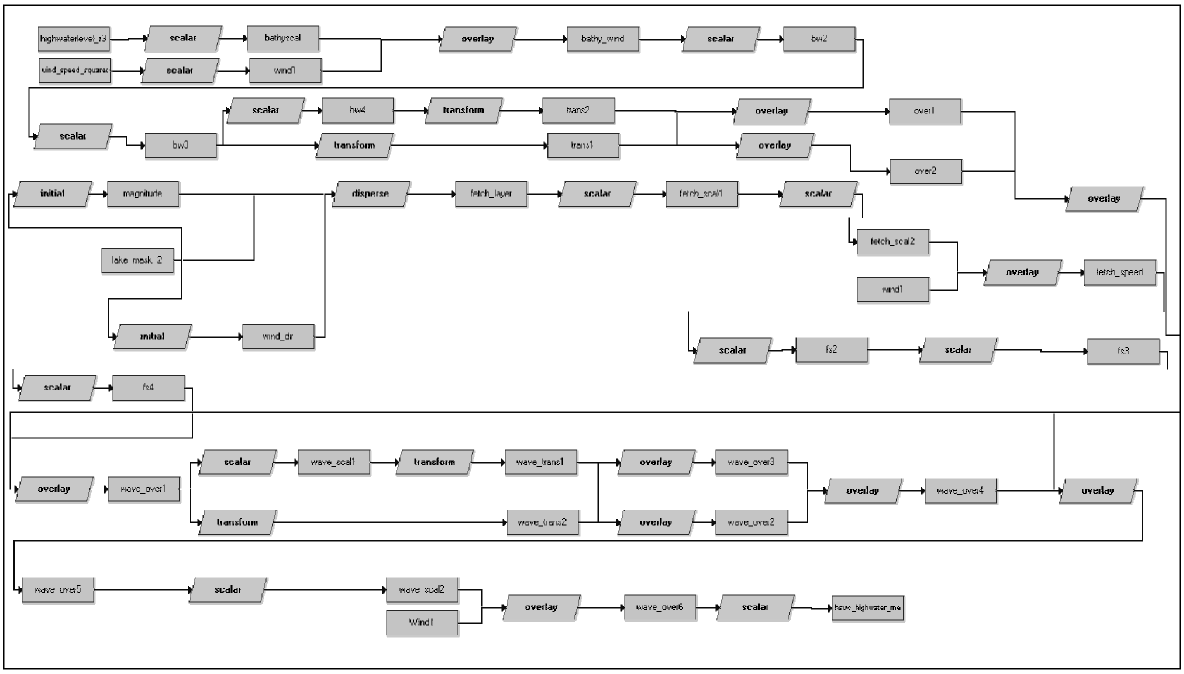
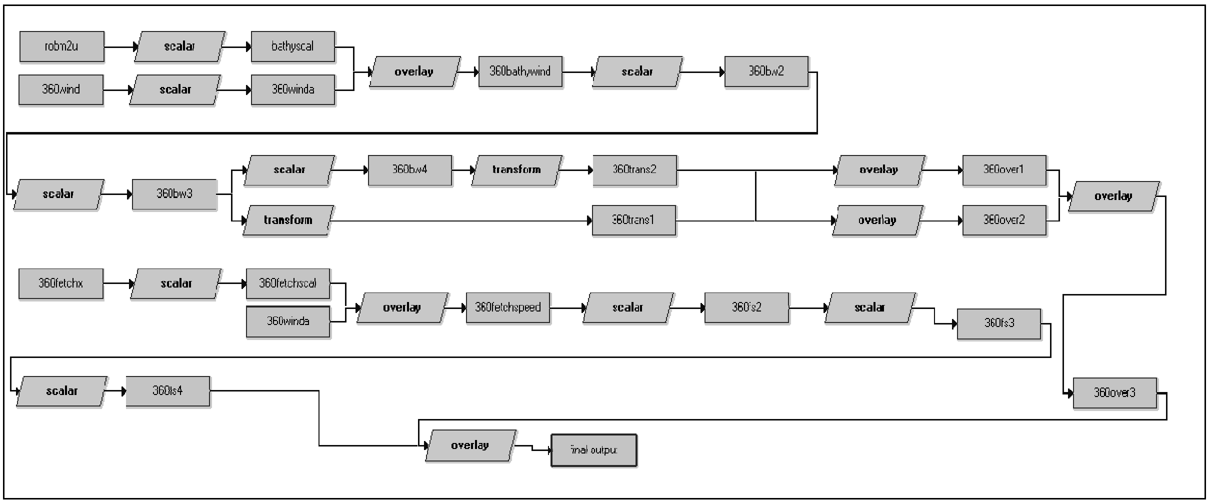
3.9 Appendix: Supplementary figures.



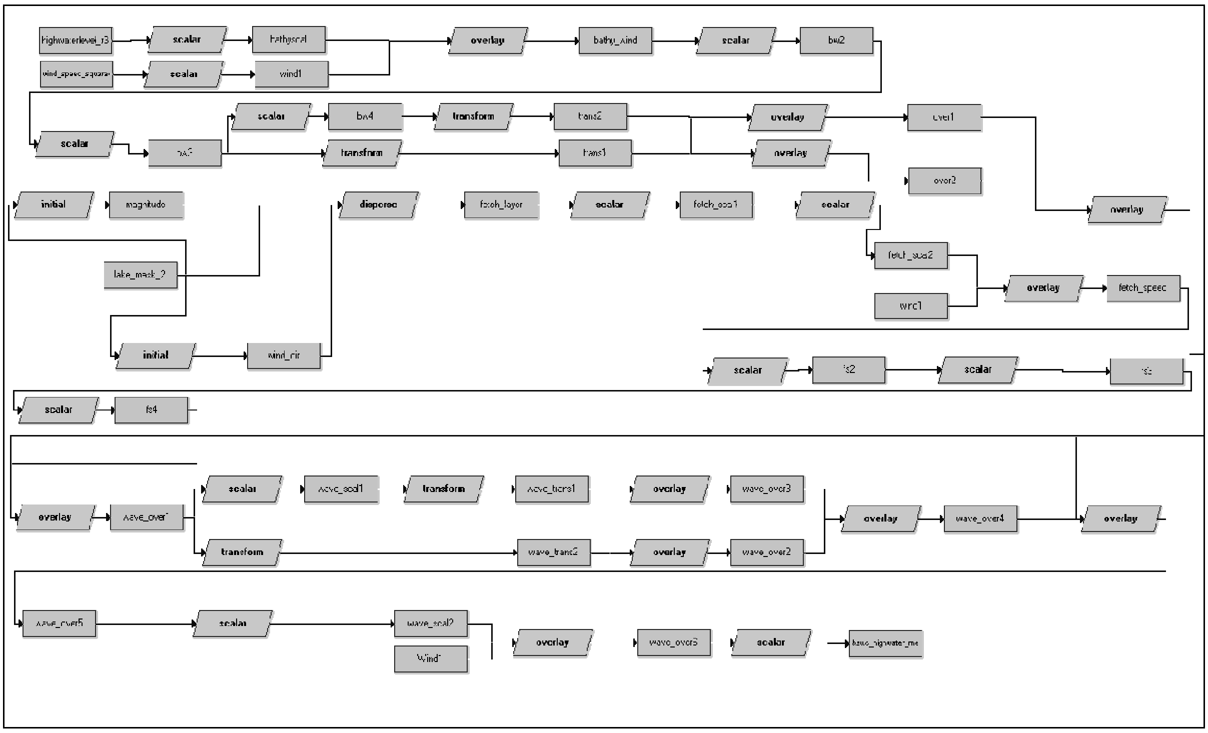
A1: Macro model implementing the calculation of fetch.



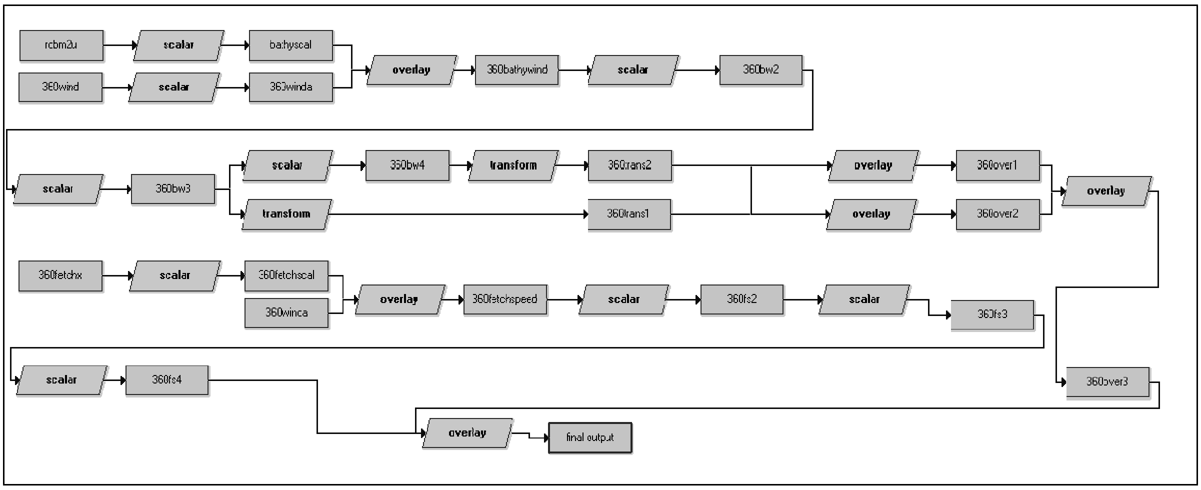
A2: Macro model implementing the adapted calculation of Shallow water significant wave height Eqn 3.



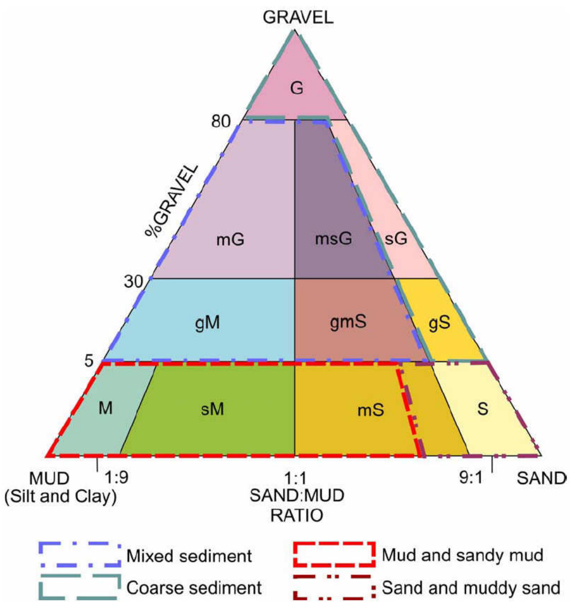
A3: Macro model implementing the adapted calculation of Deep water significant wave height Eqn 4 .



A4: Macro model implementing the adapted calculation of Shallow water significant wave period Eqn 5.



A5: Macro model implementing the adapted calculation of deep water significant wave period Eqn 6.



A6: Original reclassification for UKSeaMap by BGS.

A G.I.S FRAMEWORK FOR THE EVALUATION OF MARINE CAGE AQUACULTURE DEVELOPMENT IN THE WESTERN ISLES, SCOTLAND.

Chapter 4

Multi-site particulate dispersion modeling for marine cage aquaculture using GIS.

4.1. Introduction

Environmental Regulators have highlighted the necessity of minimizing impacts from marine cage culture to help sustain productivity and protect the marine environment (Scottish Executive, 1999). Significant impacts result from particulate organic waste, in the form of uneaten feed and faeces released during production, on the seabed in the vicinity of the cages forming a footprint effect (Beveridge, 1996). Although different opinions have been expressed regarding both the magnitude and type of aquaculture effects, there is a consensus that a gradient of diminishing impact will occur, which will vary from location to location, and that in the worst case scenario, the sediment environment under cages can become anoxic (Iwama, 1991; Karakassis *et al*, 1999). However, it is also clear that the most extreme impacts are also highly localised extending from a few to several tens of metres, and these are less likely to be significant at regional scales. The extent to which the particulate dispersion pattern has a degrading impact on the surrounding environment is thought to have a maximum radius of approximately one hundred metres from the cages (Holmer, 1991; Pearson and Black, 2000).

Previous particulate dispersion models for fish culture have been developed to forecast loading and distribution of various forms of solid waste from fish farms. These use a variety of spatial resolutions and computer software applications to investigate zones of impact of the seabed near to the cages (Gowen *et al*., 1989; Silvert, 1992, 1994; Telfer, 1995; Walls, 1996; Hevia *et al*., 1996; Dudley *et al*., 2000; Cromey *et al.,* 2002; Corner *et al*, 2006). Most models predict direct impacts over time and distance, though some also predict sediment recovery times for marine farm sites (Morrisey *et al,* 2000), to estimate the length of fallowing time necessary for the effects of fish farming to be within acceptable limits. A number these models, including the Aquaculture Waste Transport Simulator – AWATS - (Dudley et al., 2000) and DEPOMOD (Cromey *et al*, 2002) combine hydrodynamics and waste dispersion models to provide first-order estimates of the physical dispersion of finfish aquaculture wastes. These can be used to provide environmental regulators with quantitative information to enable informed decisions to be made when licensing of new marine fish farm developments are considered.

Far-field particulate dispersion of aquaculture waste has been investigated using highly complex three dimensional hydrodynamic models for salmon farming (Dudley, 2000) and integrated multi-trophic aquaculture (Ferreira *et al*, 2009). This work is still in its infancy but shows that although some particulate waste is taken beyond the immediate area of the fish cages, it has not been shown to cause significant impacts on seabed sediments. To date, none of this work has fully addressed the multi-site impacts of fish cage farming.

The Institute of Aquaculture, at the University of Stirling has been developing waste dispersion models since the early 1990's (Telfer, 1995). These models have evolved and developed from simple spreadsheet-based calculations giving 2 dimensional coordinates (Telfer, 1995), through to more complex spreadsheet modeling that incorporates bathymetry as a further dimension and re-distribution of waste post-settlement using GIS functions (Walls, 1996; Perez et al, 2002, Kimber, 2007). More recently, these models have been fully integrated into a GIS framework using supplementary coding through a Borland Delphi interface which enables routines to be run from within GIS for ease of data entry and manipulation and for controlling spatial modeling subroutines within the GIS software (Brooker, 2002; Corner *et al*, 2006). There are a number of advantages to be gained from including the outputs from waste dispersal modeling within the GIS framework. The main ones being the ability to use the extensive spatial modeling and data manipulation capability of the GIS software and the ability to incorporate such impact models into complete decision support systems for integrated coastal zone management (Hunter *et al*, 2007).

The Western Isles, off the west coast of the Scottish mainland, has a large marine salmon industry with a total of 87 active fish farm sites. Several of these are multi-site, having more than one cage block in a single area, with the potential for a combined and increased relative impact on the local environments. There is a large diversity of marine habitats and areas that are important for marine conservation present within the Western Isles. Thus, both the extent of the dispersion and the combined effect of waste from a number of sites may be important in assessing the overall effect on these important or sensitive habitats and sub-littoral communities.

This study investigates the development and use of simple GIS-based dispersion modelling for prediction of particulate distribution patterns at multiple aquaculture sites in defined loch systems. This will enable the incorporation of waste impacts from marine cage aquaculture into a comprehensive GIS framework and decision support system.

4.2 Particulate Dispersion Model components and Development

4.2.1 Initial model development (Spreadsheets)

Initial model development steps focused on a spreadsheet model (Telfer, 1995: Walls, 1996). This spreadsheet model can create a basic footprint which calculates the two-dimensional north (Y) and east (X) coordinates for "packets" of food or faecal waste for each individual current speed and direction reading, using the simple dispersion equations from Gowen et. al. (1989), where:

$$X = \frac{d(V \sin\theta)}{u} \quad \text{and} \quad Y = \frac{d(V \cos\theta)}{u}$$ …………………………….. Eqn 1 & Eqn 2

For d = water depth (m), V = current speed (ms^{-1}), θ = current direction (deg grid-N) and u = settling velocity of food or faecal particle (ms^{-1}).

Fish production data for twenty five of the eighty seven active fish farms was supplied from SEPA for the Western Isles and incorporated into the spreadsheet model. Hydrographic data was in the format required by the Scottish Environment Protection Agency (SEPA) for environmental regulation of fish farms (SEPA, 2007). This was recorded as 60 sec averaged at 20 min intervals over a 15 day period for current speed (m/s) and direction (deg grid N). Data was collected near the surface, at mid-water and near the seabed within 100 m of the centre of the cage site.

The resulting footprint created within this spreadsheet could then be imported into GIS and following manipulation could be incorporated into a GIS framework. Whilst the results from the spreadsheet were valid it was restrictive in that it could not be applied to multiple sites simultaneously, as each site required a separately parameterized run of the model and this did not fit well with the concept of a multi-site GIS approach.

Subsequently, a more complex spreadsheet particulate model was developed (Kimber, 2007) which was an adaptation of previous work carried out by Perez et al, 2002; Brooker 2002 and Corner *et al*, 2006. The spreadsheet calculations were created in four workbooks. Each individual workbook represents calculations for initial data input, cages, bathymetry and final feed and faeces dispersion calculations and results which emulated that developed by Corner *et al* 2006. The spreadsheet model calculated initial quantities of discharged food and faecal material and their horizontal displacement due to water currents using a mass balance approach with hydrographic and bathymetric data. The spreadsheet integrated results can then be exported to GIS and give a final waste distribution outcome within a 500m^2 area surrounding fish farm. Representative output examples can be seen in Fig. 4.1. for the two differing sites.

The "Complex Spreadsheet model", quantified solid waste released, calculated the distribution of wastes and generated waste plots using IDRISI using a scientifically robust methodology which has been validated to the industry standard Depomod with an overall accuracy of +10.5%. However due to the increased complexity, requirement for large amounts of detailed data and the long processing time required, this spreadsheet was unable to be used simultaneously for multi sites.

Although both spreadsheet dispersion models generate detailed high quality predictions of dispersion patterns of potential wastes from fish cages, their complexity and lack of structure to incorporate multi site modeling means that this approach was therefore not suited for inclusion in a holistic GIS model.

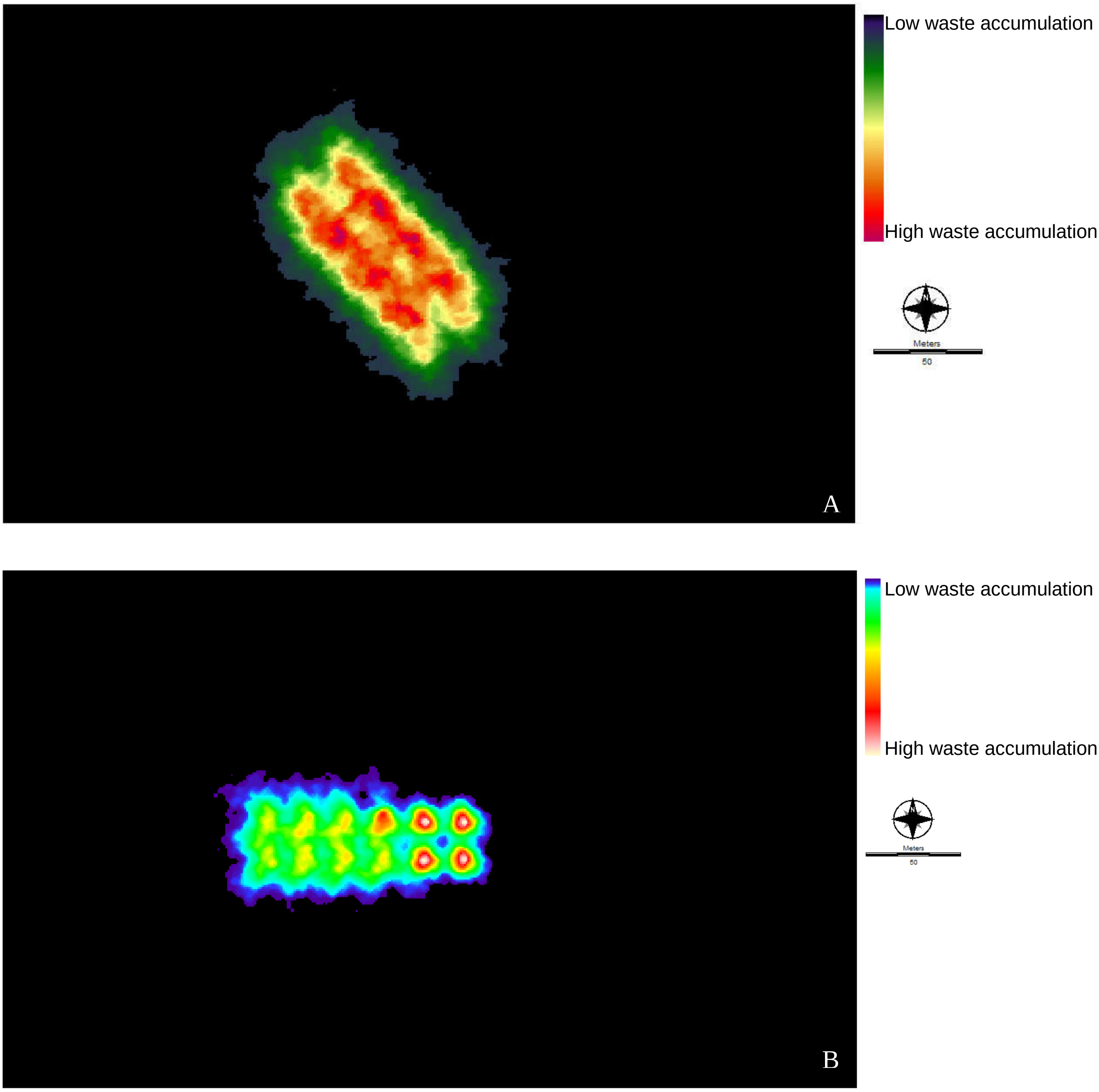


Fig 4.1 Waste dispersion models from a) Grierham Farm and b) Totarol Farm using the "Complex" spreadsheet model.

4.2.2 GIS dispersion model

Currently Scotland has a narrow focused approach to particulate waste dispersion from fish cages (Telfer *et al*, 2009), the model designed in this study aimed to model particulate dispersion patterns from fish farms on a multi site level implementing the hydrodynamic variables of the local environment. A much simpler approach was finally adopted in which a particulate dispersion model was developed which operated totally within the IDRISI

(Clark labs) environment and which required no external component. Aquaculture activities will release particulate material in to the environment in the form of uneaten feed and faecal matter and this release of particulate into the environment can negatively degrade it (Iwama, 1991; Naylor *et al*., 2000; Mirto *et al*., 2002; Holmer *et al*., 2003; Wilson *et al*., 2004; Cancemi *et al*., 2006). Particulate dispersion patterns from aquaculture activities are thought to be mainly influenced by local current velocities, bathymetric profile, farm production values, settling velocities, cage movements and resuspension (Cromey *et al*, 2002; Doglioli *et al*, 2004; Corner *et al* 2006; Giles *et al*, 2009). The main environmental variables implemented in this model are bathymetric profile and maximum current velocity.

4.2.3 Depth

Digital depth vector data was sourced from the British Geographical Survey (DigiBath250, 2005). It was further refined through interpolation to create a raster-based bathymetric map at 1 m pixel resolution and geo-referenced to UTM 29n matching the rest of the data base. A full bathymetric surface was interpolated from this data. For incorporation into the disperse model in the macro model this layer had to be reclassified to represent the image values as forces.

4.2.4 Current velocity

Data availability on maximum current velocity was sparse and for this reason, point data from numerous sources was collected from SEPA, University of Stirling environmental studies department and UKDMAP which were then combined in a point vector file. The information was further refined through triangular network surface interpolation procedures to create a raster surface image at 1m pixel resolution and geo-referenced to UTM 29n. For incorporation into the dispersion model in the macro model this layer had to be reclassified to represent the image values as forces.

4.2.5 Model structure

The final, much simpler, modeling approach adopted was based upon cost surface and dispersion techniques which are native to many GIS systems. Successful implementation of cost-spreading techniques can be seen in a range of diverse studies such as determining routes for forest access roads (Dean 1997), wildfire spread paths (Heimiller and Dean, 1998) analyzing networks of blood vessels in medical imagery (Olabarriaga *et al*. 2003) and determining ocean surface winds (Felicisimo *et al*, 2008). The principles and concepts of practical anisotropic cost spreading are described by Huriot *et al* 1989 and Smith 1989. The common assumption in any cost dispersion analysis study is that the traversing costs are a known factor. The approach adopted here considers that any particulates emerging from a fish farm do not have a motive force of their own, but are acted upon by anisotropic forces and frictions to disperse them over time. The cost modelling requires information on the magnitudes of forces (direction) and frictions (current velocity and bathymetric profile) as these are the most likely to affect particulate dispersion for fish cages. Anisotropic cost analysis implementation in the study of particulate dispersion patterns from fish cages on a multisite level uses the modules Cost, which calculates a distance/proximity surface, and Disperse, which models movement caused by anisotropic forces in terms of direction and magnitude but that have no motive force of their own. Each force (maximum current velocity and bathymetric profile) was explored individually. Clearly, although both of these environmental factors are important, the major aim is to create a model that is simple, user friendly and does not require a vast amount of detailed data whilst still producing scientifically valid results.

A particulate distribution model was developed to operate wholly within the IDRISI Andes (Clark Labs) GIS environment (Fig 4.2) by implementing Anisotropic cost analysis using a macro model. This combined a variety of inbuilt modules which are capable of determining the cost of movement of particles released from fish farms, where the cost of moving is a function of the environmental hydrological factors described as frictions and forces that impede or aid the particulate movement. A source map identifies a source cell or cells, in this case representing fish cages, that will be used as the starting point for the anisotropic cost analysis and so the initial steps for the model were the creation of a polygon raster layer representing all active fish farm cages within the study area. This source map and the cost surface and directional images were then combined using DISPERSE to generate the final particulate sub-model. The dispersion model operates in a 2-dimensional aquatic environment where the particulates released from the farm sites are assumed to be neutral buoyant and distributed in a horizontal manner. DISPERSE models the movement of a phenomenon which do not have motive force by its own, but moves due to forces that act upon it (Eastman, 2003). Forces and frictions act upon particulates released from fish cages and in this study two are explored; an interpolated maximum current velocity or an interpolated bathymetric profile where their values are reclassified relative to the assumed fixed base cost. When reclassifying the initial force/friction images, forces are expressed as values less than 1 (the base cost) and these values will facilitate movement whereas frictions are expressed in value greater than 1, which will impede particulate movement.

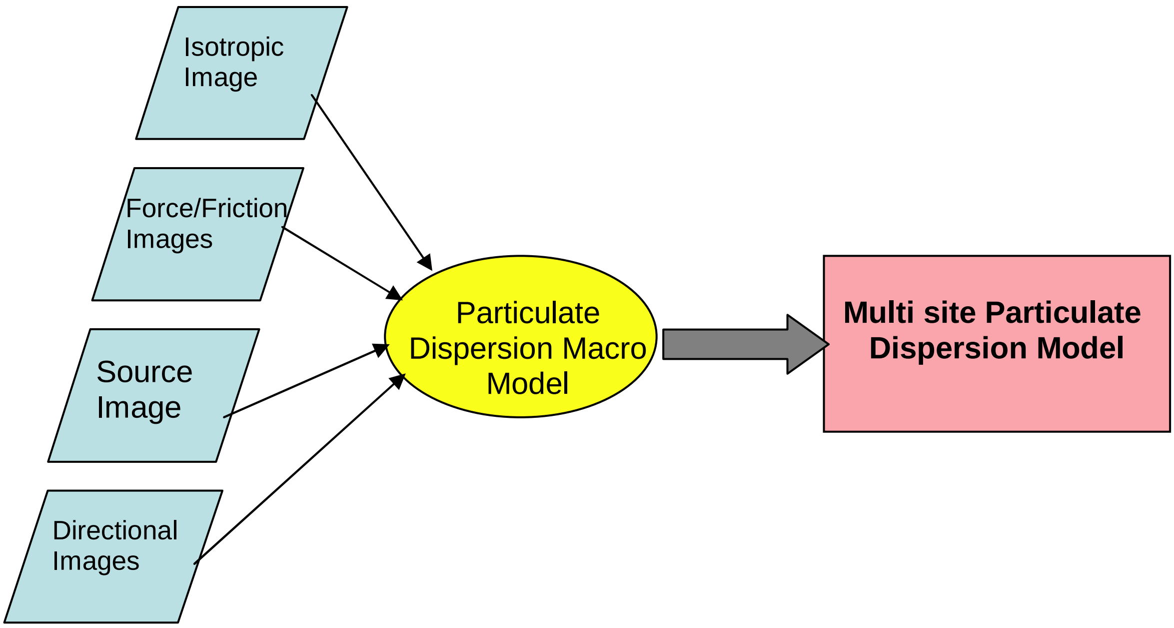


Fig.4.2 Diagrammatic representation of particulate dispersion model developed wholly within GIS environment.

The dispersion module also incorporates an isotropic cost surface representative of the aquatic environment indicated by a value of 1 while the land is indicated with a value of 1000 which allows for the distinction of absolute coastline barriers to particulate movement. The last parameter defined within the dispersion module is the type of anisotropic exponent to be implemented and this affects the extent that a force acts in varying directions. It was considered appropriate to use the default cosine function of 2 where the resulting pattern of dispersion resembles a plume, due to the decreasing probability of movement as one moves in any direction away from the maximum force direction. This plume pattern is assumed to be correct, and is an example of how the exponent affects the dispersion of particulates from fish cages.

The dispersion model was tested at a number of resolutions, from 1 to 30m for two farm sites, A and B and using maximum surface current velocity or depth as the dispersive forces (Figs 4.3, 4.4; Tables 4.1, 4.2). The results clearly indicate that modelling at thirty metre resolution regardless of the type of force image clearly results in a high over estimate of the dispersion pattern, whilst modelling at the five metre resolution using either force image also results in highly over estimating the dispersion pattern. The two metre resolution for the depth force image produced an acceptable dispersion pattern for Site A but not for Site B. The two metre resolution model for the force image maximum current speed does create a clearly understandable result but still shows a slight over estimation. Overall, it was considered that dispersion with a one metre resolution was most appropriate for further investigation of farm sites.

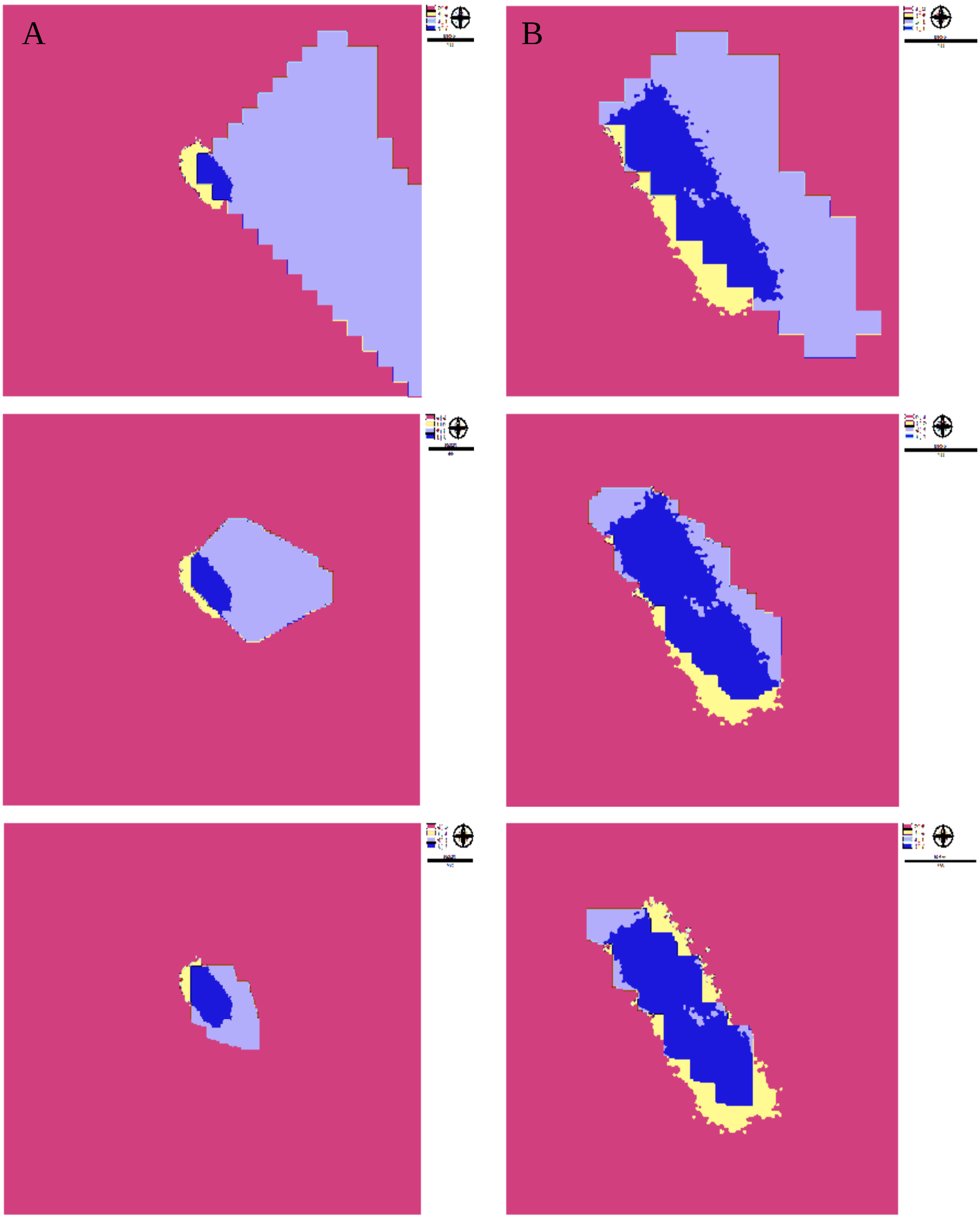


Fig.4.3 Illustrates for sites A and B Crosstabulation which combines the results from the complex spreadsheet waste dispersion model and the GIS particulate dispersion models. Regions shown in dark blue demonstrate the area of congruence when combining the two models. Yellow areas in the image represent spreadsheet results only, lilac areas

represent GIS dispersion only and lastly pink indicates background area. The top image resolution is 30m, middle image resolution is 5m, and the bottom resolution is 2m.
and the GIS dispersion driving force is maximum current velocity.

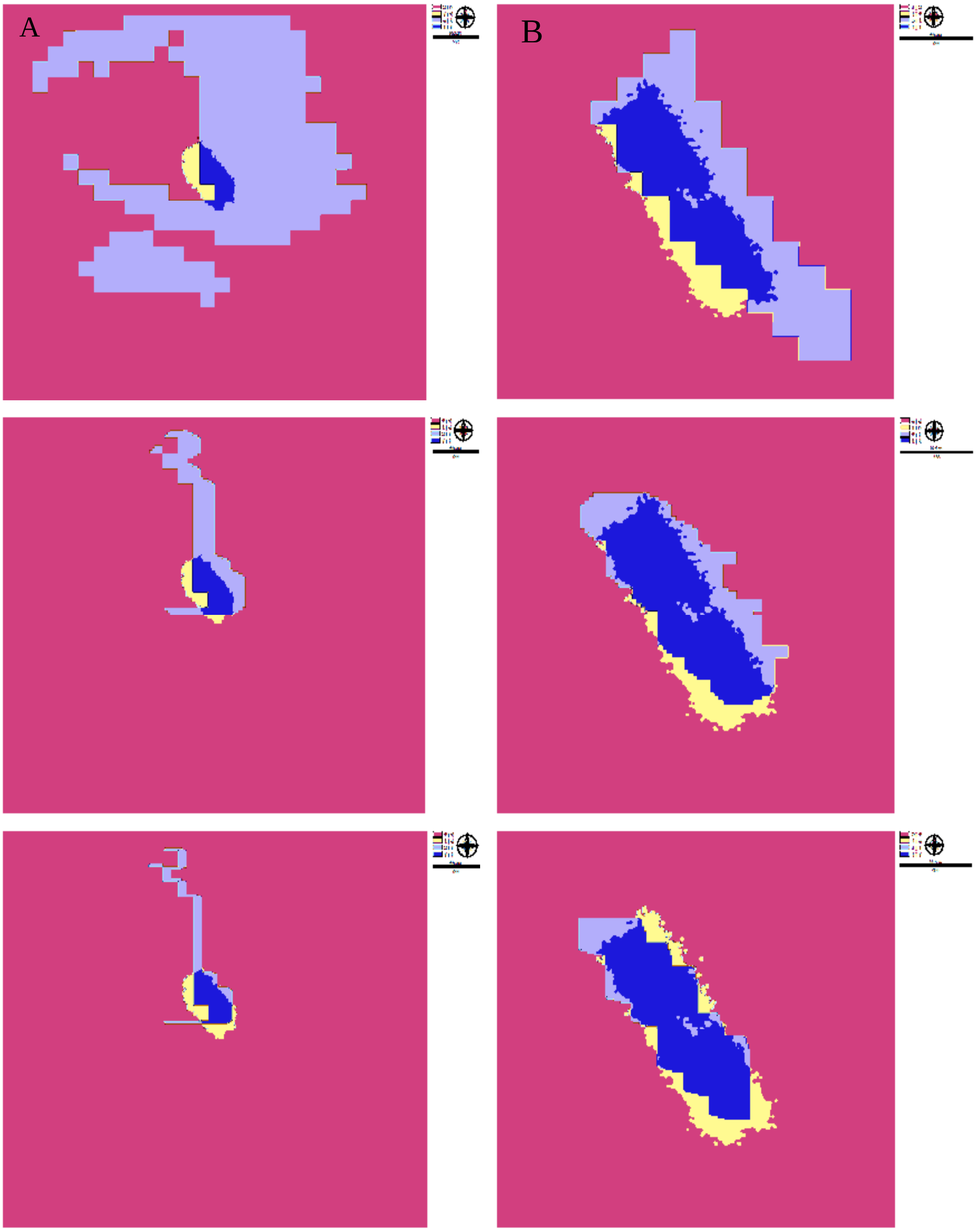


Fig.4.4 Illustrates for sites A and B Crosstabulation which combines the results from the complex spreadsheet waste dispersion model and the GIS particulate dispersion models. Regions shown in dark blue demonstrate the area of congruence when combining the two models. Yellow areas in the image represent spreadsheet results only, lilac areas

represent GIS dispersion only and lastly pink indicates background area. The top image resolution is 30m, middle image resolution is 5m, and the bottom resolution is 2m. and the GIS dispersion driving force is depth.

Table 4.1 Crosstabulation statistical results for Farm site A implementing either the maximum current velocity at 30m, 5m, and 2m or Depth at 30m, 5m and 2m.

Resolution	Chi-Square	DF	P-Level	Cramer's V	Overall Kappa
Maximum Current velocity					
30	39753	1	0.000	0.3988	0.3200
5	117279	1	0.000	0.6849	0.6702
2	109697	1	0.000	0.6743	0.6739
Depth					
30	69588	1	0.000	0.5276	0.4810
5	117190	1	0.000	0.6847	0.6687
2	113679	1	0.000	0.6624	0.6623

Table 4.2 Crosstabulation statistical results for Farm site B implementing either the maximum current velocity at 30m, 5m, and 2m or Depth at 30m, 5m and 2m.

Resolution	Chi-Square	DF	P-Level	Cramer's V	Overall Kappa
Maximum Current velocity					
30	2224	1	0.000	0.0943	0.0353
5	20371	1	0.000	0.2855	0.2047
2	70125	1	0.000	0.5296	0.5054
Depth					
30	961	1	-0.000	0.0620	0.0232
5	42267	1	0.000	0.4112	0.3677
2	56408	1	0.000	0.5010	0.5000

Further investigations were carried out to investigate the value of implementing either actual cage polygons to represent each individual fish cage at a farm site,or one main polygon to represent the farm site as a whole. It was clear that the dispersion pattern was not greatly influenced by using either. The choice was dictated by the time it takes to vectorise individual cages compared to one main representative of the dispersion area. The main premise behind this model is that it must be user friendly and for this reason the use of one main polygon was chosen.

The particulate GIS dispersion macro model was applied to all the farm sites in the four principal fjord systems for the Western Isles at 1m resolution on a multi site basis.

4.3. Results

4.3.1 GIS Particulate Dispersion model

Within the fjord systems modelled for particulate dispersion, there are a range of active fish farms which vary in cage sizes and production levels. The environmental conditions of the four fjords modelled differ as some are in sheltered environments while others are more hydrodynamic. The model does not quantify waste dispersion onto the seabed sediments, rather, it indicates the predicted positions of settled particulates released, which is indicative of the footprint of distribution from the fish cages. The predicted particulate dispersion loading for the main fjord systems are shown in Figs. 4.5 to 4.12 using maximum current velocity and depth as the forcing image, respectively.

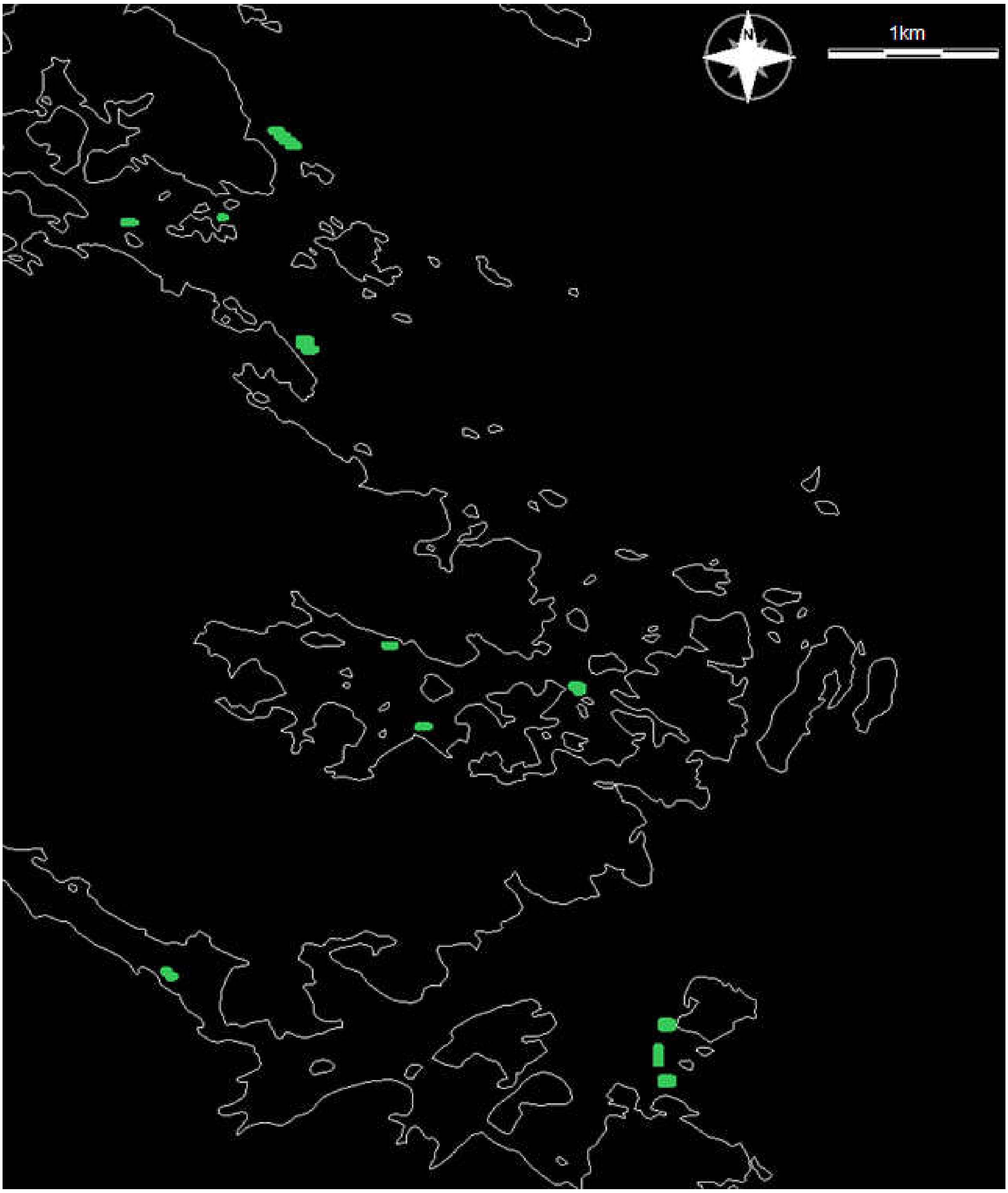


Fig 4.5. GIS-based particulate dispersion model for Loch Skiport and Baghnam Faoileann Fjord systems using maximum surface velocity as the forcing image at a resolution of 1m.

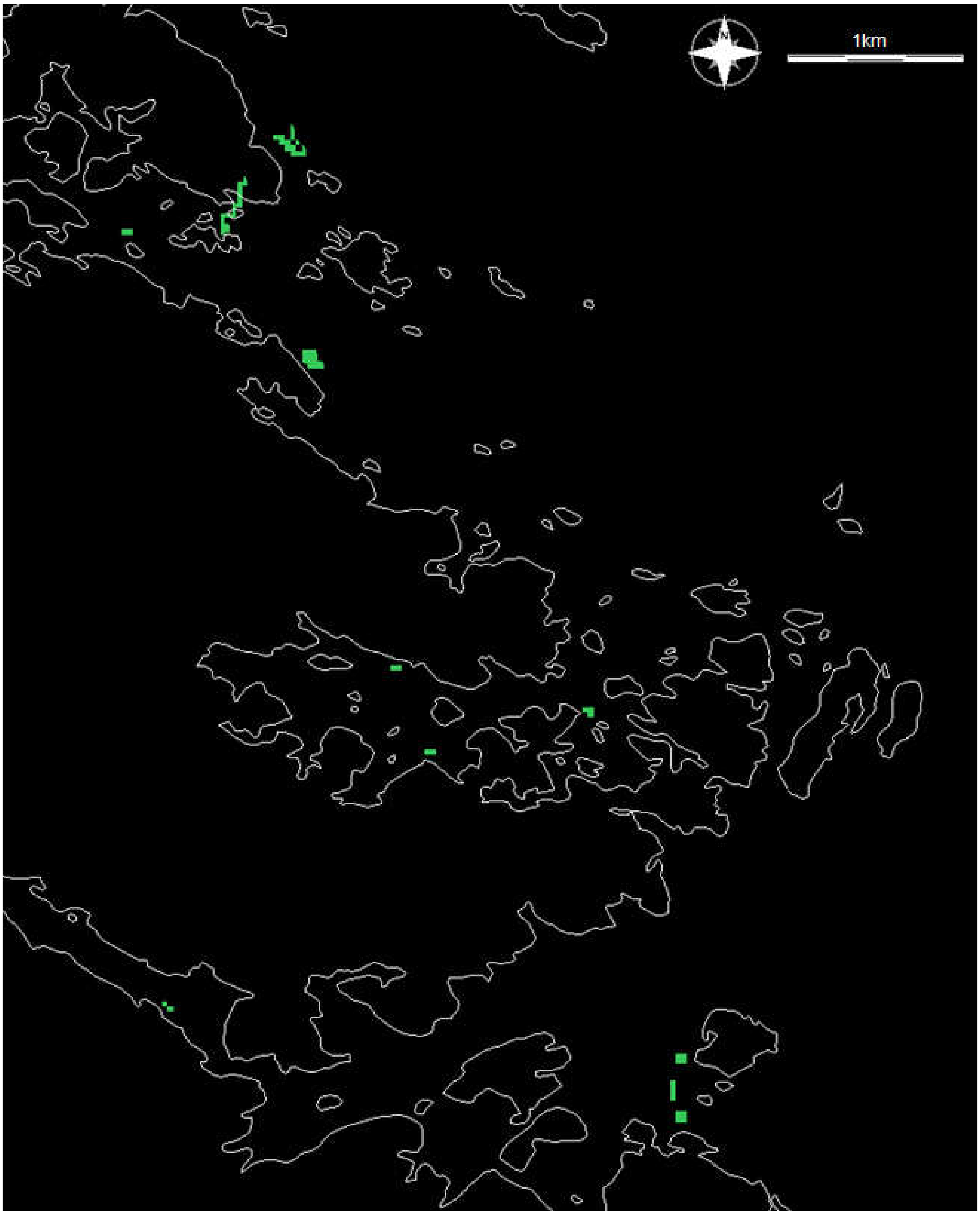


Fig 4.6. GIS-based particulate dispersion model for Loch Skiport and Baghnam Faoileann Fjord systems using depth as the forcing image at a resolution of 1m.

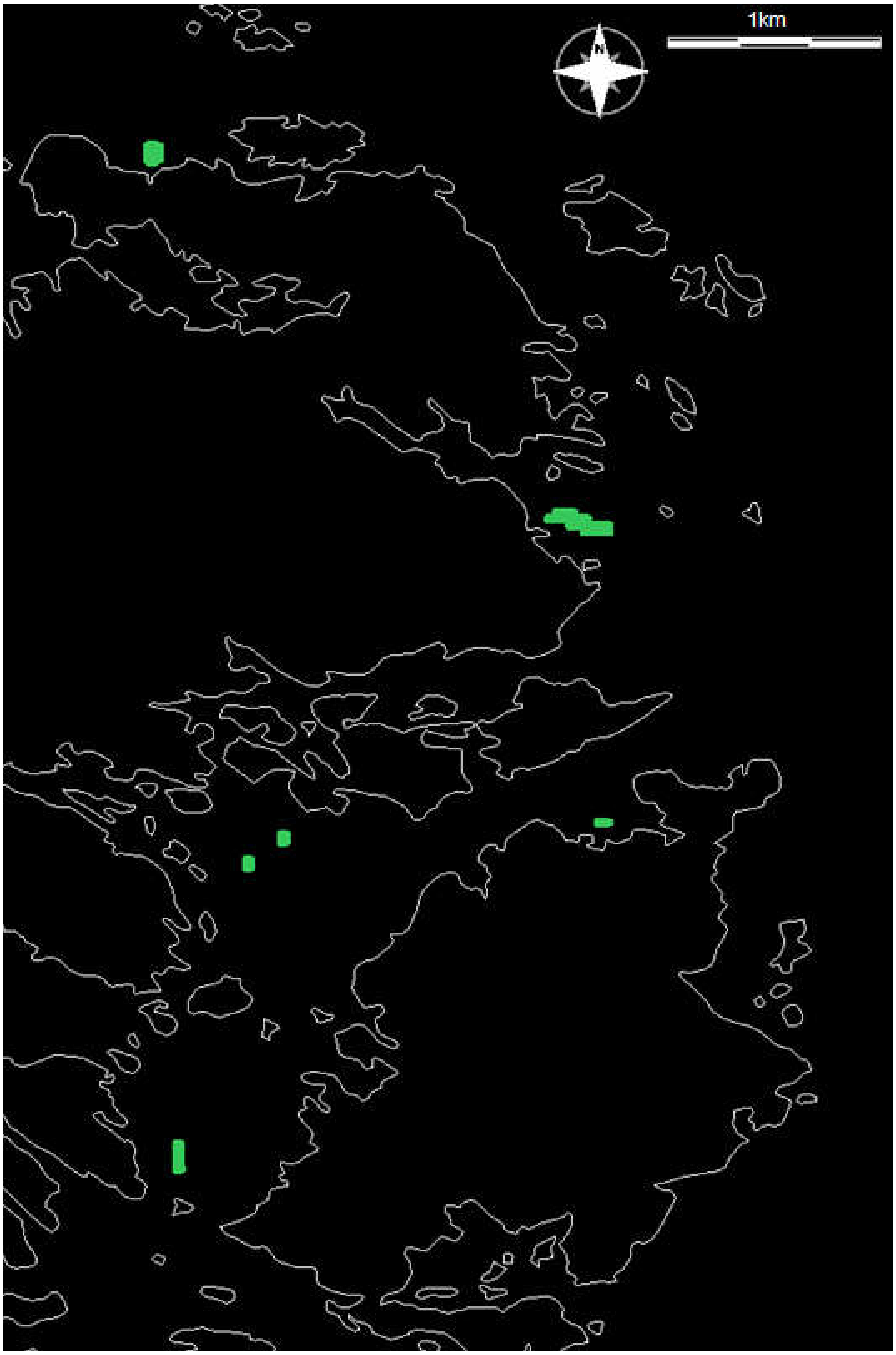


Fig 4.7. GIS-based particulate dispersion model for East Benbecula Fjord system using maximum surface velocity as the forcing image at a resolution of 1m.

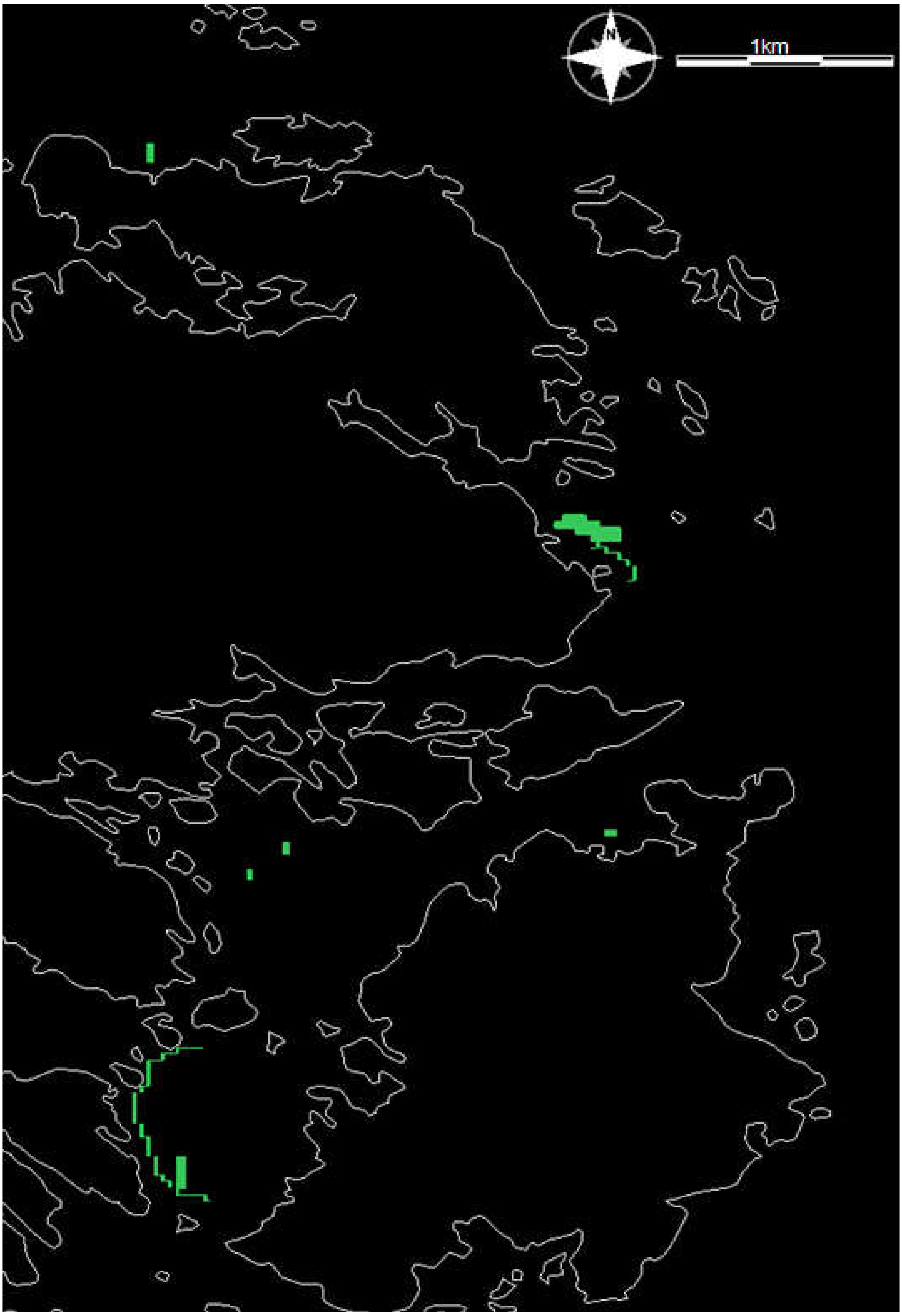


Fig 4.8.GIS-based particulate dispersion model for East Benbecula Fjord system using depth as the forcing image at a resolution of 1m.

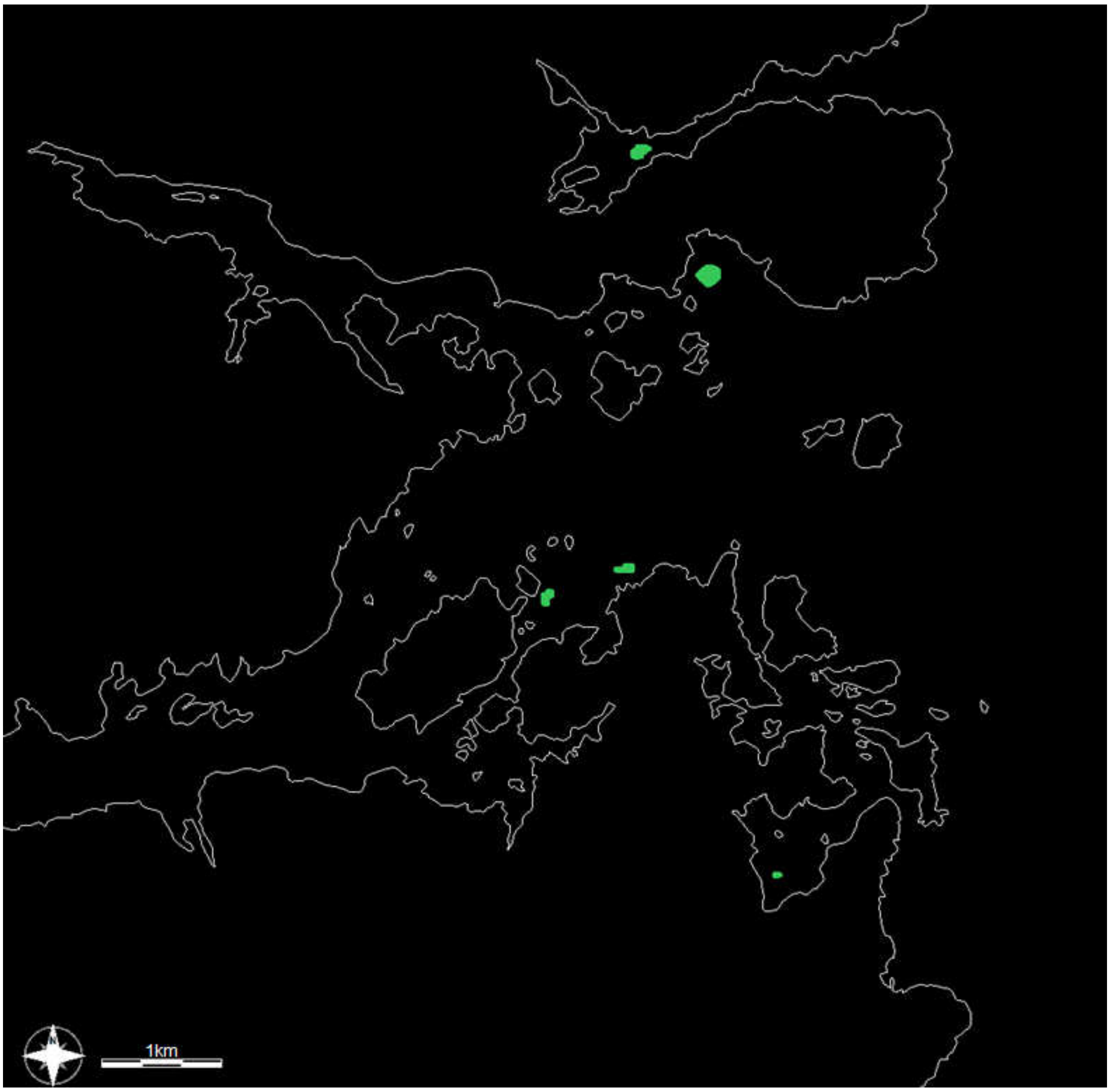


Fig 4.9.GIS-based particulate dispersion model forLoch Erisort and Loch Leurbost Fjord system using maximum surface velocity as the forcing image at a resolution of 1m.

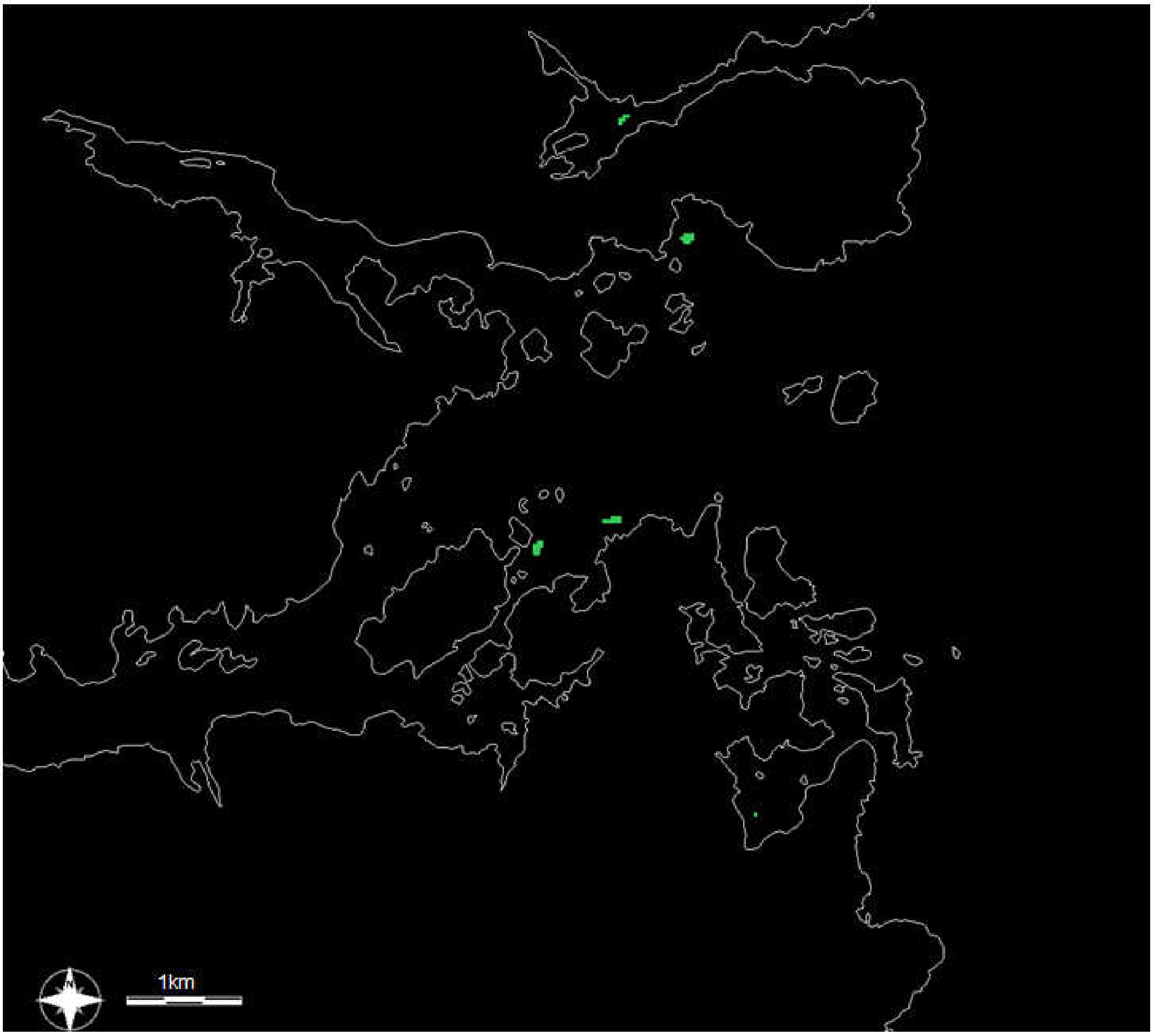


Fig 4.10. GIS-based particulate dispersion model for Loch Erisort and Loch Leurbost Fjord system using depth as the forcing image at a resolution of 1m.

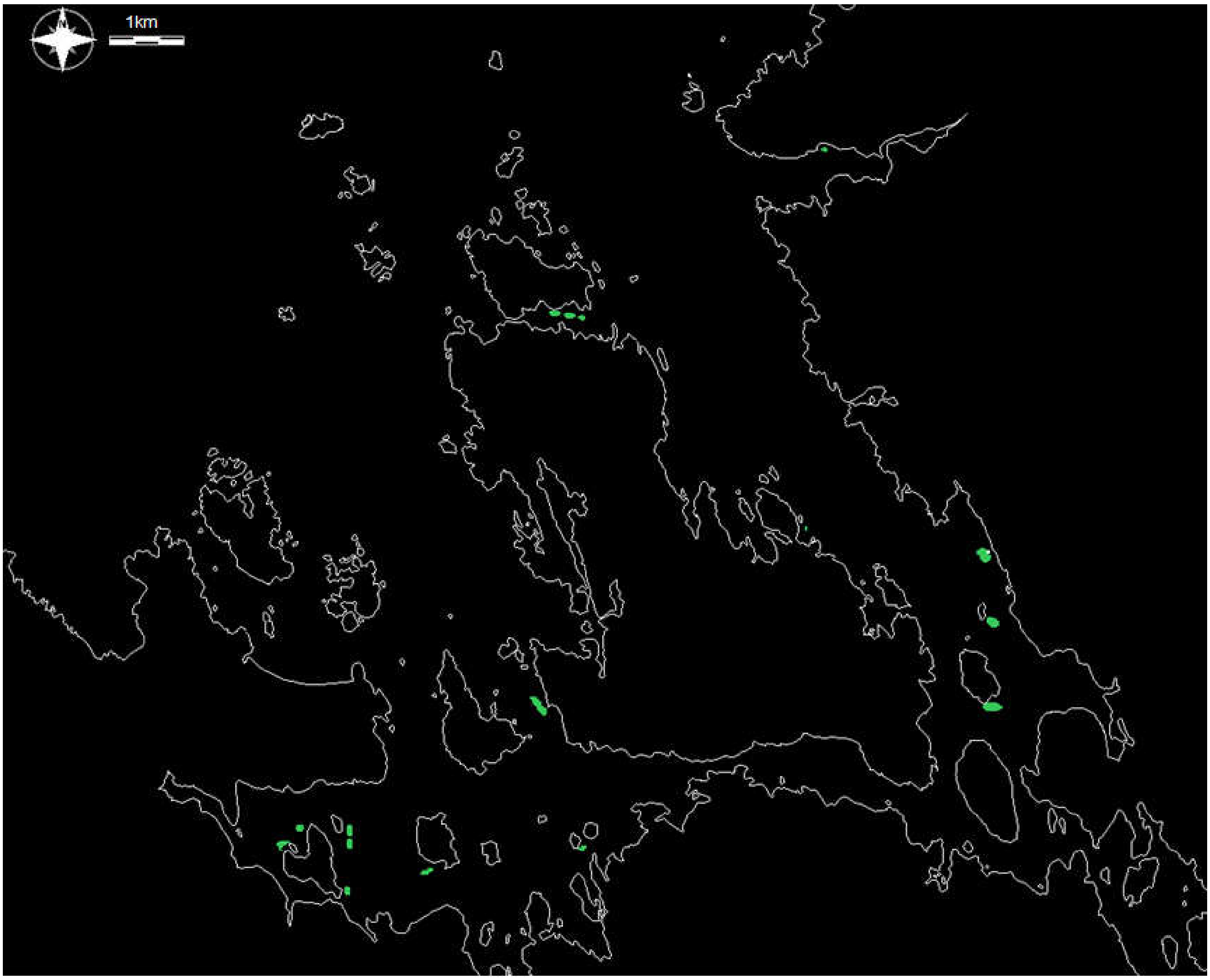


Fig 4.11. GIS-based particulate dispersion model for Loch Roag Fjord system using maximum surface velocity as the forcing image at a resolution of 1m.

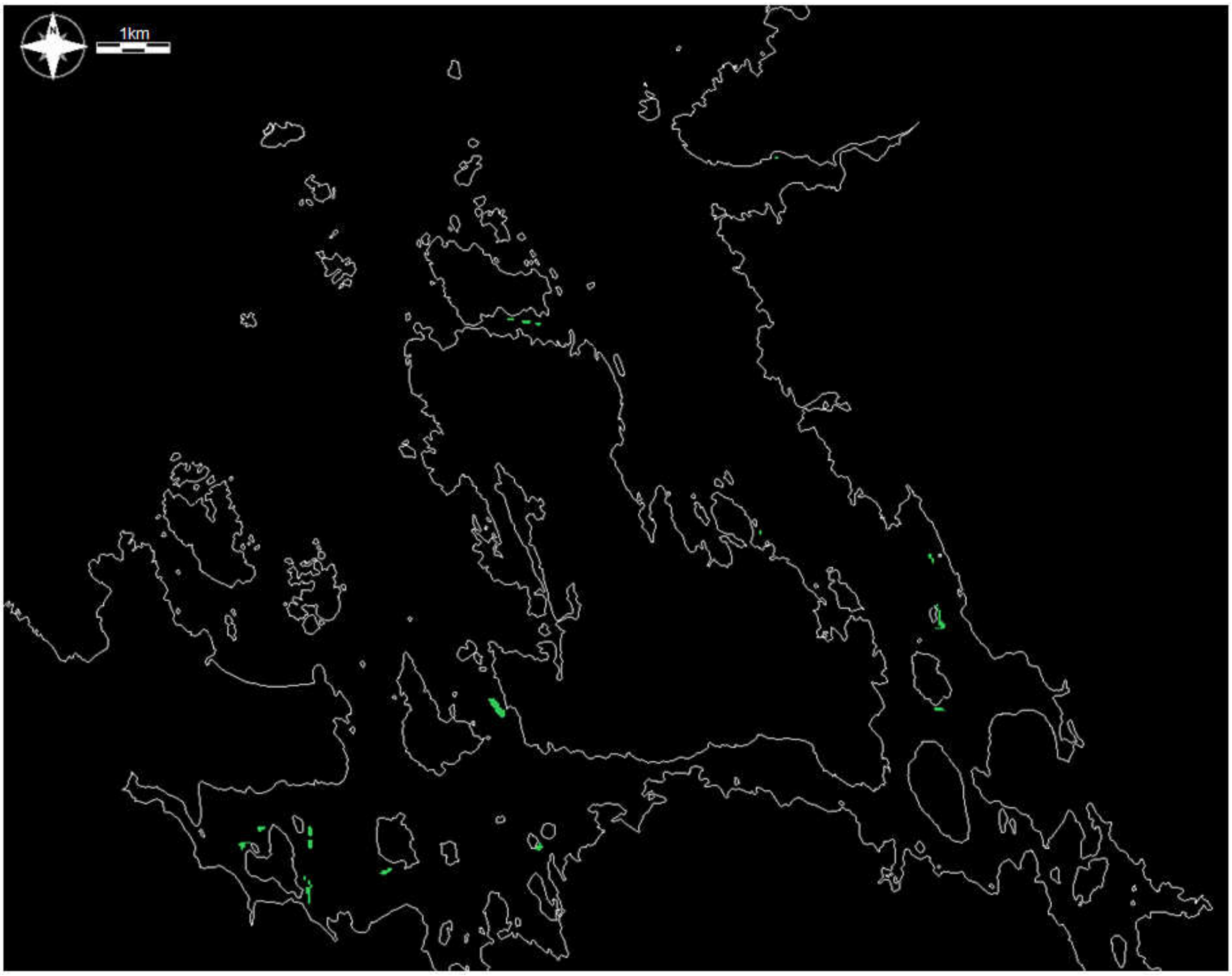


Fig 4.12. GIS-based particulate dispersion model for Loch Roag Fjord system using depth as the forcing image at a resolution of 1m.

Loch Skiport and Baghnam Faoileann Fjord Systems (Figs. 4.5 & 4.6).

Force/Friction Image Maximum Current Velocity:

The resulting multi site particulate sub-model indicates that the outer farms have a larger dispersion pattern in comparison to the farms located in more sheltered areas of the fjord system which display a smaller dispersion pattern.

Force/Friction Image Bathymetric Profile:

This sub-model indicates that there is an issue with the base force friction image. As can be clearly seen this force/friction image develops a completely unrealistic dispersal pattern.

East Benbecula Fjord System (Figs. 4.7 & 4.8).

Force/Friction Image Maximum Current Velocity:

The resulting multi site particulate sub-model indicates a prominent eastern dispersion pattern from all farms within this fjord system.

Force/Friction Image Bathymetric Profile:

It is interesting to note that the resulting multi site particulate sub-model indicates a very restricted dispersion pattern and also evident is its development in an unrealistic dispersal pattern.

Loch Erisort and Loch Leurbost Fjord Systems (Figs. 4.9 & 4.10).

Force/Friction Image Maximum Current Velocity:

The resulting multi site particulate sub-model indicates an interesting dispersion pattern where the farms in the northern part of the Fjord have a greater dispersion pattern when compared with those in the sheltered south part of the fjord system.

Force/Friction Image Bathymetric Profile:

The resulting multi site particulate sub-model indicates a similar pattern of dispersion to that found using the Maximum Current Velocity. However, it should be noted that this is on a much restricted scale.

Loch Roag Fjord System (Figs. 4.11 & 4.12).

Force/Friction Image Maximum Current Velocity:

The resulting multi site particulate sub-model indicates that the farms on the Eastern side of the fjord system tend to disperse wastes over a wide area while those on the Western side of the system are much less dispersive. It should be noted that throughout the fjord system, even where farm sites are close neighbours, there appears to be minimal interaction in the particulate dispersion from these farms.

Force/Friction Image Bathymetric Profile:

The resulting multi site particulate sub-model indicates a similar pattern of dispersion where the farms on the Eastern side of the fjord system tend to disperse wastes over a wide area. Those on the Western side of the system are much less dispersive. However two farms have dispersion patterns which are obviously unrealistic.

Further exploration of the bathymetric data found that the coastline (a nominal 0m contour) is based on the World Vector Shoreline NIMA. This has an accuracy of 90% of all identifiable shoreline features which are located within 500 meters circular error of their true geographic positions with respect to the preferred datum (WGS 84). It is assumed that this coarseness of shoreline is the probable cause for the unrealistic patterns of dispersion which emerged. This coarseness will have an impact on the reclassification of the bathymetric profile and in the determination of the forces and frictions acting upon the particulates. Fig.4.13 shows how there is a likelihood that some farms will be indicated as being on land and the resulting force will be equal to the base, when clearly this is not the true nature of the case.

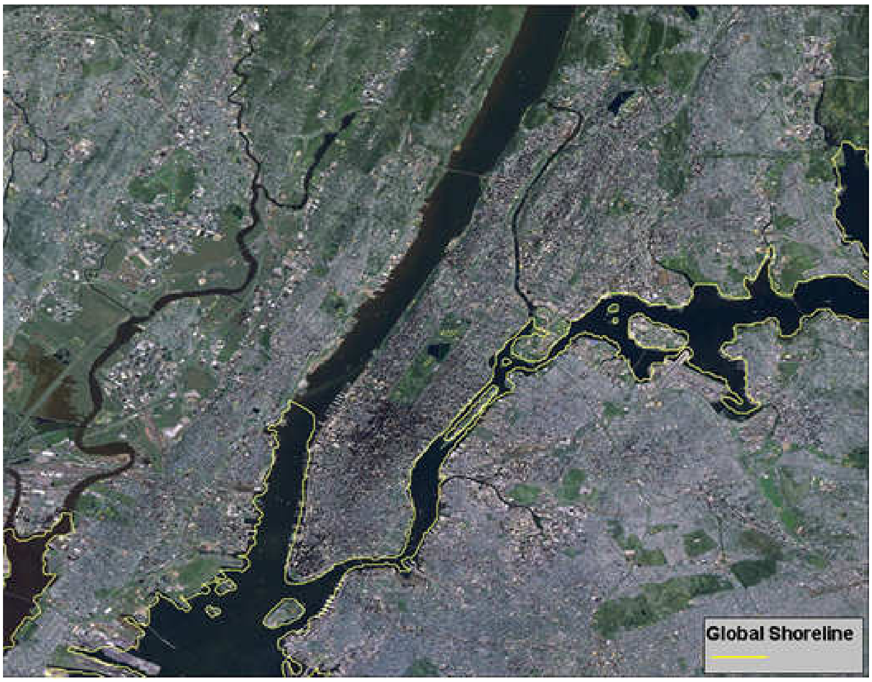


Fig.4.13 The scale of the global shoreline depicted in this graphic is approximately 1:250,000 or greater. The scale of the imagery is approximately 1:130,000. Notice the coarseness of the shoreline detail compared to the LANDSAT image.

4.4 GIS Waste Dispersion Model Partial Validations

Partial validation of the GIS Waste Dispersion model was achieved by comparison of the modelled outputs with that for other dispersion models for the same finfish cage sites.

Two farms were chosen from Loch Roag; 1) Site A, on the Western side of the loch where cages had a high biomass in a fast water current and deeper water site and, 2) Site B, on the Eastern side of the loch a small cage system with low biomass, in shallow water (this is a slow flow site). These farm sites were modelled using a complex particulate spreadsheet model, which is an adaption of the Corner et al (2006) model. The corresponding results from these farms were extracted from the GIS model and were "windowed out" for comparison between methods. For statistical analysis, all images were converted to Boolean patterns for comparison through Cross tabulation which compares and quantifies coincidence between images containing categorical variables of two types. There are a number of possible ways to do this and the one implemented here is by Hard classification with a full cross-tabulation expressed in terms of proportion of total number of pixels. In addition to a range of statistical measures, this technique also generates an image displaying the overlapping dispersion areas from the two models.

The comparison of sites and methods is shown in Figs 4.14 and 4.15 and the statistical summary in Table 4.3. The two most important statistical results are the Overall Kappa index and the Cramer's V. Overall Kappa is an index of agreement between two input images as a whole which measures associations between two input images. If the two input images are in perfect agreement (no difference) Kappa will equal 1 whereas if the two images are completely different, Kappa will have a value of -1. Cramer's V coefficient indicates the relationship between two categorical variables which also ranges from -1 to 1 with 0 indicating no relationship and 1 indicating a perfect relationship.

4.5 Overall Findings

The crosstabulation results indicate that the maximum current velocity at both sites is more strongly correlated with the validated waste dispersion pattern than the bathymetric profile friction/force image. Interestingly, if further sites were to be validated it is evident that this correlation would be much less for the bathymetric profile as some of the dispersion patterns exhibited in Fig. 4.6 and Fig. 4.8. are not logical. The issues experienced with the bathymetric profile friction/force image have been identified and are caused by the coarse shoreline resolution. It would be appropriate to explore the bathymetric profile with a better coastline imagery. Overall the most practical application of multi site particulate modeling from fish farms is by implementation of maximum current velocity at a one metre resolution.

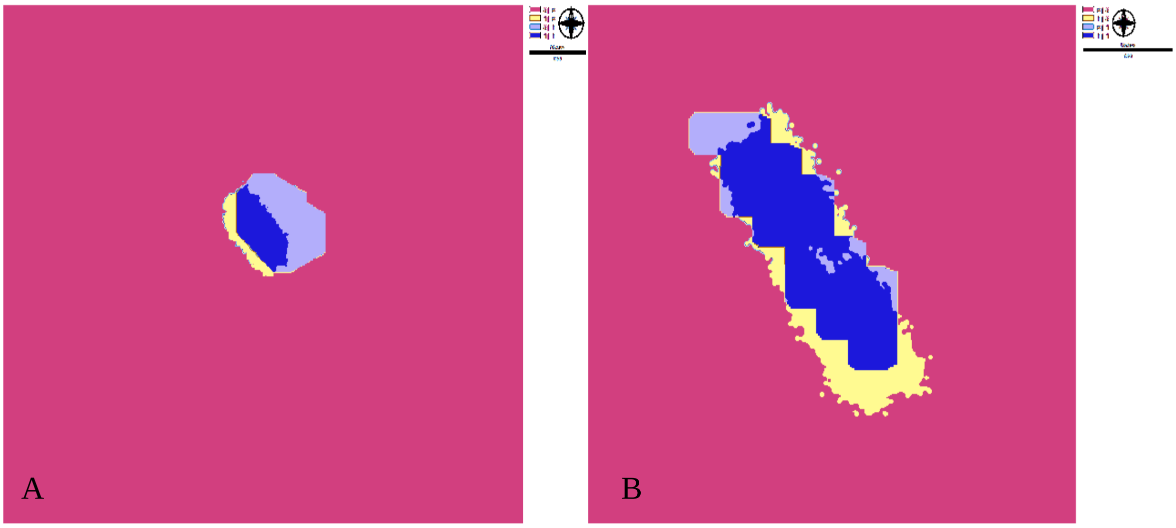


Fig.4.14 Illustrates for sites A and B a Crosstabulation which combines the results from the complex spreadsheet waste dispersion model and the GIS particulate dispersion models. Regions shown in dark blue demonstrate the area of congruence when combining the two models. Yellow areas in the image represent spreadsheet results only, lilac areas represent GIS dispersion only and lastly pink indicates background area. Dispersion predicted by both models is at 1m resolution and the GIS dispersion driving force is maximum current velocity.

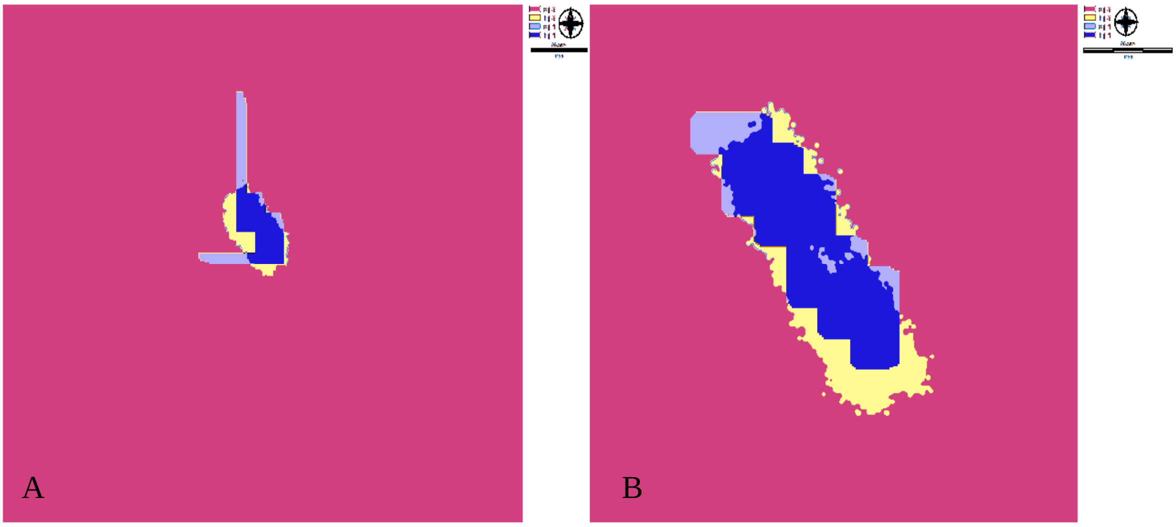


Fig.4.15 Illustrates for sites A and B a Crosstabulation which combines the results from the complex spreadsheet waste dispersion model and the GIS particulate dispersion models. Regions shown in dark blue demonstrate the area of congruence when combining the two models. Yellow areas in the image represent spreadsheet results only, lilac areas represent GIS dispersion only and lastly pink indicates background area. Dispersion predicted by both models is at 1m resolution and the GIS dispersion driving force is depth.

Table 4.3 Crosstabulation statistical results for Farm sites A and B, using maximum current velocity or depth as the driving force behind the particulate movement.

Farm Site	Chi-Square	DF	P-Level	Cramer's V	Overall Kappa
Maximum Current velocity					
A	109899	1	0.0000	0.6630	0.6630
B	79815	1	0.000	0.5650	0.5251
Depth					
A	109809	1	0.000	0.6627	0.6627
B	67196	1	0.000	0.5184	0.5154

4.6 Discussion

Waste production from aquaculture activities are probably perceived to be one of the most controversial and detrimental impacts of aquaculture on the environment. Whilst the literature is conflicting in terms of the magnitude of the effect, it has been proposed that these impacts may not be as detrimental as has previously been considered and that ,as only a small fraction of the total nutrients that are added to coastal waters, this is likely to be well within the assimilative capacity of the environment (Black, 2001). Tett and Edwards (2002) concluded that, in Scotland, for the coastal waters and sea lochs that are enriched with anthropogenic nutrients from a range of sources, including aquaculture, physical limiting factors e.g. light and biological limiting factors such as grazing prevent the occurrence of undesirable disturbance in almost all well-documented cases. However, degradation has been considered by some to be escalating on a global scale (UNEP, 1982; Choi *et al*, 2005; Norkko *et al*, 2006; Halpern *et al*, 2008). All these recent finds should be the driving force in the development of an effective modeling tool that deals with aquaculture in the environment on a wider scale than is currently being implemented.

Currently Depomod (Cromley *et al* 2000) is implemented in Scotland by SEPA, and elsewhere. This is used to model appropriate biomass limits and possible impact zones for fish farm sites. The modules integrated in Depomod are a grid generation module, particulate tracking model, resuspension and carbon degradation module, a benthic module and an in-feed medicine treatment module. The data requirements for Depomod include cage position and bathymetry, station position, current velocities and direction; feed input data, water content and digestibility of food, food and faecal settling velocities and loss of food. The resulting outputs of Depomod are a flux of deposited solids, total deposition of solids in a specified time period and the predication of macro benthos descriptors. Whilst Depomod it clearly has strengths, its' weakness lie in the non-homogenous spatial distribution of currents, it also doesn't include shoreline effects and wind-wave resuspension is not tested on hard substrates nor does it consider the water column effects. There is a current need for a stronger modeling tool which is scientifically robust and suitable for all governing agencies and stakeholders to implement.

This study focused on aquaculture production discharges of particulates into the environment. Once these particulates are in the environment they will be dispersed and then assimilated by the environment. This assimilation can be predicted and is dependent on the hydrographic conditions, bathymetry and natural features of an area (Provost, 1996). The models implemented here aims to adequately replicate local environmental conditions so as to enable the definition of impacts from multi-site aquaculture production.

The extent of the study area illustrated here for the Western Isles highlights the potential complex interactions between aquaculture activities in sea lochs and the need for a wider scale approach. Also, on a wider level, there is a need to be able to assess aquaculture and all its components on a more holistic level, for example, one that can incorporate considerations of site suitability and many other factors. GIS has the capability to take waste modeling forward, and can provide a clear foundation for creating a more powerful and robust tool that is easy to replicate, is rapidly updatable and can be policy-driven in its application.

Initial model developments focused on a particulate waste dispersion model through a spreadsheet which can be successfully imported into a GIS environment. The final spreadsheet model incorporates background carbon, cage movement and is at a 1m resolution. The flexibility of the model allowing the user to predict waste deposition over any production time scale, demonstrates its versatility, but incorporates some major assumptions. The hydrographic measurements recorded over 15 days, representing a full spring-neap tidal cycle are ideal for predicting the waste dispersion over the same 15 days. However, this data is also used to represent the hydrography over an entire production cycle, which will naturally vary by season and with varying storm events. The requirement of the model to set a percentage of feed wasted is another fixed assumption, which, in reality could have a high degree of variability within the production cycle. The variability originates from the husbandry, involving the quality of staff, stress level of the fish, occurrence of disease and the use of computerized feeding systems (Corner et. al. 2006). These assumptions could be addressed by incorporating extensive hydrographic data sets and variable predictions of feed loss, but the data would be expensive to collect and the model may potentially become too complex. This natural variability of parameters emphasizes the fact that a model is a simplified depiction of reality used to simulate a process and it is important that any model does not become over complicated. The main limitations of the waste dispersion model include the use of constant horizontal current, no account for the loss of carbon from the system and the requirement to transfer data between spreadsheet and GIS. The incorporation of variable horizontal currents can only be achieved using current meters deployed at different locations around the site, which currently is too expensive for the purposes of routine regulation.

Any particulate dispersed from a fish cage is influenced by depth, velocity, resuspension and a rate of decay, this pattern of dispersion has been the subject of extensive discussion (Cromley *et al*, 2002; Perez *et al*, 2002: Corner *et al*, 2006). DEPOMOD and other techniques are based upon this background. The complexity arising around the spreadsheet models led to a focus in study to a wholly GIS environment for a particulate dispersal model developed in a multi site manner for particulate dispersal, fully georeferenced and at a one metre resolution which is better than the 10m resolution obtained from DEPOMOD (Cromley *et. al.* 2002).

This model is developed as an editable macro model, which is simple to parameterise, easy to operate and is very efficient in terms of processing power and time. The strength of the particulate cost analysis dispersion model developed here is its ability to investigate the complex process of particulate dispersion. Ultimately the outcome was validated and produces an understandable result which can be further explored in a holistic GIS model for aquaculture.

This study has demonstrated that multisite modelling is possible wholly with a GIS environment. Fig. 4.16 shows the predicted particulate footprint from three adjacent farms using the rapid model method developed here. It is interesting to note that, even when in close proximity there seems to be limited overlap in footprints. While this may apply to solid wastes, it will not be the same for dissolved wastes or for biological components such as sea lice larvae. This stage was an exploratory exercise to determine the results and further possibilities of using a wholly GIS integrated dispersion model.

The current simulation time unit of the model is 1 hour however the model is set up in such a manner that this time period can be increased and explored further with feed back loops that can be carried on throughout an entire simulation period that will result in a range of dispersion images with respective start and end points that can be combined for a final model. Another major adjustment of the model will be the introduction of quantifying carbon values to the dispersion patterns. With further refinements, this model will further expand the capabilities of current waste dispersal modelling and potentially has numerous positive benefits for the regulation of the aquaculture industry.

A current limitation of this modelling approach is that it does not quantify the waste outputs. Future developments of this macro model would benefit from the incorporation of some of the quantitative aspects of the more complex spreadsheet model (Corner *et al*, 2006***)*** without adding greatly to data requirements. While the resulting macro will inevitably have a similar complexity to that for wave climates (Chapter 3) it should not greatly increase the processing time as the user would only be required to be concerned with manipulating the input fields it should therefore retain its current user-friendliness.

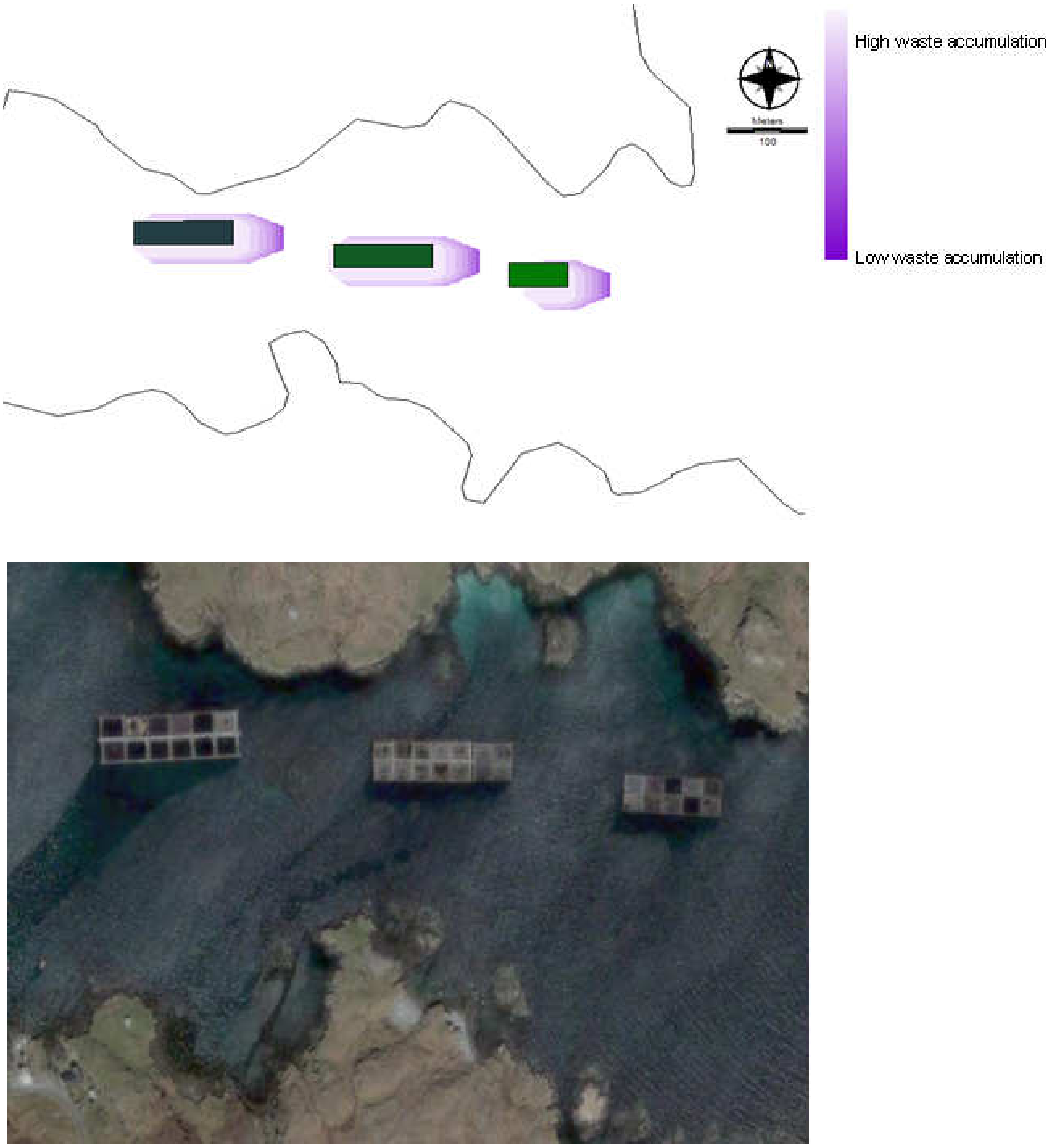


Fig.4.16 Representative example of multisite waste GIS dispersion model. The LANDSAT image shows three adjacent farms, while the image above shows their predicted waste footprints.

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Chapter 5

A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Modelling Marine Biodiversity sensitivity to support marine cage aquaculture site selection.

Donna-Claire Hunter, Fiona Miller, Trevor C Telfer and Lindsay G Ross.

This chapter describes the application of GIS for the improvement of aquaculture resource management by identifying and analyzing important Biodiversity areas for the Western Isles, Scotland. This has been recognized as a potential area for conflict with coastal aquaculture activities, and this conflict requires to be understood and minimized in order to ensure that important habitats and species are conserved while not impeding the development of aquaculture as an important production activity.

The body of the text is presented as a publication-ready manuscript. However, an Appendix is also provided which contains additional supporting information and figures which, though not constituting part of the submitted journal article, are an essential component that underpins the thesis.

The main author, D-C Hunter, developed the GIS-based Biodiversity model using species distribution and habitat suitability modules. Fiona Miller developed the process for extracting the relevant binary data from the downloaded data from the National Biodiversity Network website and digitizing these data as part of her BSc Marine Biology research. Lindsay Ross and Trevor Telfer provided PhD supervisory support and contributed to editing the document.

This manuscript has been submitted to *Ecological Indicators.* This journal seeks to integrate the monitoring and assessment of ecological and environmental indicators with management practices.

Modelling Marine Biodiversity sensitivity to support marine cage aquaculture site selection.

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Abstract

The purpose of this study was to develop a GIS-based spatial model to show the distribution of important regions for biodiversity in coastal areas of the Western Isles, Scotland. The area is host to a wide variety of diverse habitats and species but is also a significant area for aquaculture in Scotland. Geographical Information Systems were used to develop species distribution and habitat suitability models to establish the interaction of biodiversity with aquaculture and the potential consequences for aquaculture development. A number of biodiversity indicators of sensitivity were included in the model, including endangered species, species sensitive to aquaculture, protected areas, fish spawning and nursery areas and species important to the Western Isles. The combination of these layers through multi-criterion evaluation (MCE) and further ranking, highlighted areas of low and high biodiversity sensitivity and the consequences that aquaculture development would have on the biodiversity of the area. The final Biodiversity sensitivity model indicates that the Western Isles has 1168km^2 (4% of study area) where the biodiversity is highly sensitive to aquaculture while 20595km^2 (65% of study area) has a biodiversity that is much less sensitive to aquaculture. Although this GIS model was used as a sub-model for a complete GIS-based integrated coastal zone model for aquaculture site selection, it can operate as a "stand alone" tool or can be combined into a larger framework for more wide ranging site selection decisions. With relatively little modification and reparameterisation such models can also be developed to cover the whole of the Scottish coastline, or any other coastal locations worldwide.

Keywords
GIS modelling, marine aquaculture, biodiversity sensitivity, Species Distribution Map, Scotland.

5.1 Introduction

It has been predicted that the upward trend of aquaculture development experienced in the past ten years in Scotland is likely to continue (FRS, 2008). For this expansion to have long term sustainability there needs to be consideration of the wide ranging possible impacts on the environment that aquaculture may have. Impacts on the local environment can be direct from wastes released into the local environment or degrading the value of the landscape through aesthetic impact. The most arguable potential impact from aquaculture development is on biodiversity and this is a matter of concern both locally and in terms of compliance with the requirements of the Convention on Biodiversity (UNEP/CBD/COP/9/25/) and the broad recommendations of the Ecosystem Approach to Aquaculture (Soto *et al*, 2008).

Biodiversity assessment is well established through indicators usually based on status and trends for individual species, and identification of important habitat and has led to the increased use of species habitat modeling (Galparsoro *et al*, 2009; Rolland *et al*, 2009; Williams *et al* 2009). This single-species focus is driven by biodiversity legislation such as EC Birds Directive (79/409/EEC) and the EC Habitats Directive 92/43/EEC. Scotland currently has Biodiversity Action Plans (BAP) which are aimed at protection of habitats and species considered threatened within the UK (Angus, 1999). These focus on one hundred and fifty three priority species and forty one priority habitats that occur in Scotland that are determined to be *"taxonomically and ecologically diverse, and are likely to be sensitive to change in the ecosystems and natural processes on which they depend"* (Biodiversity Action Plans, http://www.ukbap.org.uk) In some cases this single species and priority habitat approach is a wholly appropriate management strategy but complexities can arise due to the vast amount of species and habitats needing to be considered. Thus a more appropriate approach strategy when considering developing aquaculture would be to select those biodiversity indicators which can define sensitivity to a stress, known reaction to disturbances, sensitivity to contaminants and habitat-specialists as the most appropriate indicators for management (Dale and Beyeler, 2001; Carignan and Villard, 2002, Niemei and McDonald, 2004; Niemeijer and de Groot, 2008).

The ever increasing availability of information pertaining to species and habitats of conservation concern is becoming unmanageable in its current form in terms of system status and trends analysis. This makes it particularly difficult to incorporate when developing coastal aquaculture in Scotland or elsewhere and to take impacts on biodiversity into account. Biodiversity may be assessed quantitatively and qualitatively. Normally, quantitative assessment utilizes simple measures such as species richness or more complicated univariate measures like diversity indices which take both species number and abundance of individuals into account (Krebbs, 1989). Other forms of assessment may use a variety of non-specific or specific Biodiversity Indicators which are appropriate to the locality, dataset or purpose of the study (Bubb, Jenkins and Kapos, 2005). An essential tool for conservation of biodiversity is the determination of species distribution (Cote and Reyonds, 2002: Degraer *et al*, 2008) and in particular using models for the prediction of the spatial distribution of species (Canadas *et al*, 2002; Ferguson *et al*, 2003; Hao *et al*, 2007, Calamusso, *et al*, 2008). The prediction of species distributions can be achieved through many types of statistical analytical methods (Guisan and Zimmermann, 2000; Boyce *et al*, 2002; Manly *et al,* 2002; Guisan and Thuiller, 2005; Hirzel *et al*, 2006; Redfern *et al*, 2006, Maxwell *et al*, 2009), each having its own strengths and weaknesses depending on the study requirements.

There is therefore a need for a comprehensive tool that can incorporate various aspects of biodiversity of sensitive species and habitats that is scientifically robust and which can aid effective management decisions (Mawdsley and O'Malley, 2009). Such a tool could be implemented by using spatial modeling of biodiversity indicator species distributions for marine spatial plans and coastal management (Borja *et al*., 2000, Guisan and Thuiller, 2005 and Degraer *et al*., 2008). By exploiting georeferenced data on location and distribution of sensitive species, GIS techniques can be used to identify sensitive habitats and species which can then be linked to relevant environmental variables enabling the development of a predictive model (Oliver and Wotherspoon, 2005: Chefaoui *et al*, 2005; Zhao *et al*., 2006: Schories *et al*, 2009). The resulting predictive model can indicate the potential distribution of a species within the chosen study area and this approach can help to ensure that aquaculture development has minimal effect on the sustainability of biodiversity. The implementation of such a biodiversity sensitivity model on a multi species basis would be highly advantageous for coastal management strategies while also allowing aquaculture to develop in well-defined and agreed non-sensitive areas.

This study investigates the creation of GIS models of sensitive habitats and species for the Western Isles, Scotland. In order to ensure that future aquaculture development is sustainable, steps must be taken to identify the ecologically sensitive habitats and marine species of conservation concern in the area. This will help to define and reduce potential future conflict. Prior identification of sensitive areas allows the preservation, protection and improvement of environmental quality, including the conservation of natural habitats and of wild fauna and flora that are an essential objective of general interest pursued by the European Community (Habitat's Directive 92/43/EEC). The model is part of a wider decision support system set designed to allow integration of spatial tools for multi-site aquaculture planning and management into a coastal zone management plan.

5.2 The Study Area

The chosen study area for this research was the Western Isles off the North West coast of Scotland (Fig.5.1) which has an extensive aquaculture industry, and significant potential for future growth. The five main islands of the group, Isle of Lewis, North Harris, South Harris, North Uist, Benbecula, South Uist and Barra, have a combined coastline length of 2,103km, in which there is a vast range of species and habitats some which are particularly sensitive to detrimental impacts (SNH, 2002).

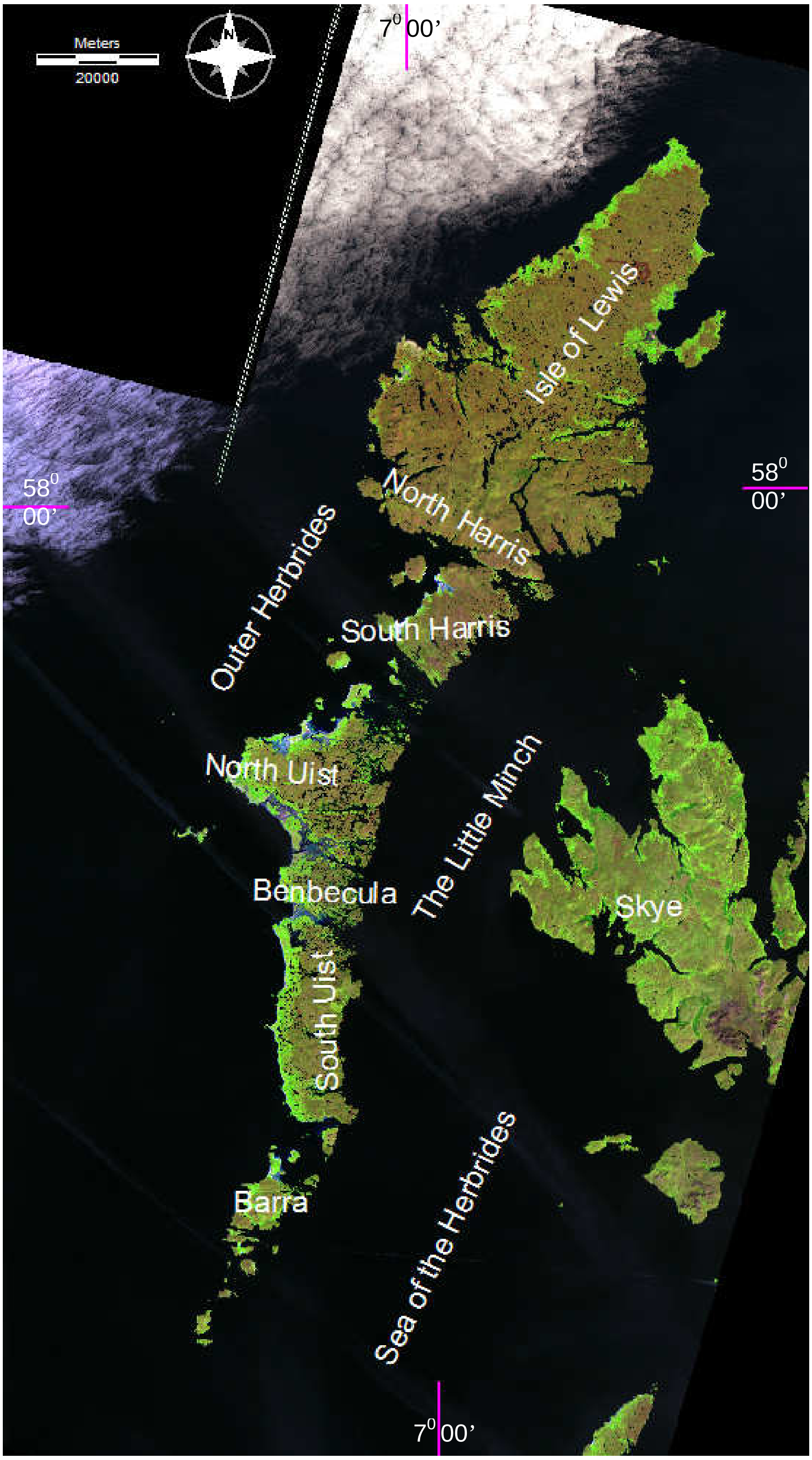

Fig.5.1 The Western Isles off the North West coast of Scotland.

5.3 Development of model components

The Biodiversity Sensitivity Model was developed from five initial sub-models representing aspects of biodiversity sensitivity which have the potential to affect aquaculture development. The initial five sub-models developed were Protected Areas, Species Sensitive to Aquaculture, Endangered species, Commercially important fish spawning and nursery areas and Species important to the Western Isles.

Species data were downloaded from the National Biodiversity Network (NBN http://www.nbn.org.uk/) database which allows viewing and download of distribution maps of UK wildlife information using a variety of interactive tools. There are currently 30,386,785 species records available on the NBN Gateway from 264 different datasets. The downloaded data is available as a spreadsheet containing data on all species identified within each $10km^2$ UK Ordinance Survey grid, which for the Western Isles requires data from 72 spreadsheets. Georeferenced data was extracted from the spreadsheets and vector polygon files were created to represent currently identified areas for each individual species (See Appendix for further details).

Protected Areas sub-model

The Western Isles has numerous national and internationally protected areas. The majority of legislated protected areas for the Western Isles occurs on land with very restricted coastal areas of Harris, Eastern coast of South Uist and the coastal zone of the Monarch Isles being protected. The SAC's that currently provide some protection for the coastline there clearly needs to be a much stronger development of these in relation to the marine environment. This apparent lack of marine protection is currently under examination and review for the U.K. (Gubbay, 2005; DEFRA 2008). While Scotland has recently introduced the Marine (Scotland) Bill on April 29, 2009. (http://www.scotland.gov.uk/Topics/Environment/16440/marine-bill-consultation).

Locations of habitats of conservation importance for the Western Isles were identified from Scottish National Heritage (SNH) data supplied as shapefiles. The supplied data was combined, reformatted and reprojected and from this, vector files were created for Ramsar sites, Special Protection Areas (SPA), Special Areas of Conservation (SAC), Sites of Special Scientific Interest (SSSI) and National Scenic Areas (NSA).

Species sensitive to aquaculture sub-model

When considering aquaculture development in the Western Isles there is a substantial risk of conflict arising and that a detrimental impact maybe experienced by the sensitive species present and clearly some species are more likely to be damaged by aquaculture than others. The Marine Life Information Network (MaRLIN) has established a database illustrating those species predominantly at risk from aquaculture practices which is based on the precept that a specific activity will impact on the environmental factors surrounding it. The MaRLIN guidelines' are that "*'Sensitivity' is dependent on the intolerance of a species or habitat to damage from an external factor and the time taken for its subsequent recovery*" (Laffoley et al**.,** 2000). By defining species which will be affected by these changes in the environment a list of species which are sensitive to that specific activity has been generated (www.marlin.ac.uk).

The key species were: the Maerls, *P. calcareum, L. coralloides and L. glaciale;* Hatchet Shell, *T. gouldi:* Common Eel Grass, *Z. marina;* Native Osyter, *O. edulis;* Horse Mussel, *M. Modiolus;* Knotted Wrack, *A. nodosum;* Lagoon Cockle, *C. glaucum;* Tall Sea Pen, *F. Quadrangularis;* Gravel Sea Cucumber, *N. mixta and the* Dog Whelk, *N. lapillus.* Distribution data on each species was extracted from the National Biodiversity Network, converted to GIS format and modeled through the Land Change Modeler (LCM) of IDRISI Andes (Clark Labs). The LCM has a number of modeling areas, but the species range polygon methodology allowed species presence polygons to be developed from original point source data, based on confidence mapping using a cluster analysis of environmental variables (A1). Again using the LCM, these refined range polygons were further developed though the Habitat Suitability and Species Distribution Model (HSSD) which involved taking the presence data through a weighted Mahalanobis typicality where a weighted means and a weighted variance–covariance matrix based on the logic of Wang (1990) was carried out. This is applied in the Mahalanobis typicality process to identify the likelihood of any image pixel being the same as or similar to the training pixels (Sangermano and Eastman 2007). The HSSD distributions developed for each species were combined by overlay addition to create the final sub-model (A2).

Endangered Species Sub-model

Endangered species are an important characteristic of biodiversity, as extinction of a certain species will affect the composition of overall biodiversity. The main factors influencing the 'critically endangered' status are habitat alteration, reduced productive capacity and overexploitation (Powles *et al*, 2000). Critically endangered species are considered at risk of extinction, and are highly protected. The IUCN red list (www.iucnredlist.org) contains data for all world-wide endangered species and provides information on threshold parameters such as; distributional range, population size, population history and includes the risk of extinction, although it is conceded that knowledge of the marine realm is imperfect and this data may be incomplete (Akcakaya *et al*, 2000, www.iucnredlist.org). Clearly, any aquaculture development should take account of the presence of such species and endeavour to minimize potential conflicts.

A detailed analysis of endangered species for the Western Isles was obtained from IUCN and from this species list the distribution of 'red-list' species in the Western Isles was extracted. The species identified as endangered in the Western Isles were: Baltic Sturgeon, *A sturio;* Freshwater Pearl Mussel, *M margaritifera:* Basking Shark, *C. maximus:* Atlantic Cod, *G. morhua:* Haddock, *M aeglefinus:* Sea urchin, *E esculentus:* Otter, *L. lutra:* and the Thornback Skate, *R clavata.* Source data on each species was processed using the species range polygon and HSSD methodology in IDRISI Andes and the layers developed for individual species were combined by overlay addition to create the final sub-model.

Commercially important fish spawning and nursery areas sub-model

In any aquaculture development there is a risk of a detrimental impact on wild fish populations. Commercial fisheries species around the Western Isles are already under considerable pressure and it was considered important to identify important habitats for commercial fisheries present in the area. . The benefits of protection of commercial fish stocks have been explored and shown to be positive (Côté *et al*. 2001; Sale *et al*., 2005) and fish spawning and nursery grounds have been identified as a conservation priority area in many studies (Roberts *et al*, 2005). Identifying nursery areas where life stage transitions take place are critical to a species population dynamics, and are therefore of particular importance for fisheries development and conservation. This is important in the Western Isles where a number of fish spawning and nursery areas occur.

Twelve commercial fish species were identified Cod (*Gadus Morhua*), Haddock (*Melanogrammus aeglefinus*), Herring (*Clupea harengus harengus*), Lemon sole (*Microstomas kitt*), Nor pout (Trisopterus esmarkii), Plaice (*Pleuronectes platessa*), Saithe (*Pollachius virens*), Sandeel (*Ammodytes marinus*), Sprat (S*prattus sprattus*), Whiting (*Merlangius merlangus*) , Blue whiting (*Micromesistius poutassou*) and Mackeral (*Scomber japonicus*). Data on spawning and nursery areas for the twelve important fishery species was obtained from the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) of the UK government in shapefile format. The data was combined, reformatted and reprojected and from this, vector files were generated. The data on each species were developed using polygon refinement and HSSD and the layers developed for each species were combined by overlay addition to create the final sub-model.

Species important for the Western Isles

From the large amount of species presence data collated during the data collection phase many were not classified as sensitive to aquaculture, vulnerable or endangered. However, they still are part of the wider biodiversity of the islands that could potentially be affected by any aquaculture developments or activities. These species which are important for the Western Isles were identified from consideration of the important tourist industry and from local Biodiversity Action Plans (http://www.cne-siar.gov.uk/biodiversity/) for the Western Isles. The current main driver for the economy for the Western Isles is tourists (HIE Innse Gall and VisitScotland, 2007).

The key species in this category were: Arctic Charr, *S. alpinus* : Bib, *T. luscus* : Brown Sea Trout*, S. trutta* : Common Seal, *P. vitulina;* Loggerhead Turtle, *C. caretta;* Leathery Turtle, *D. coriacea* : Ling, *M. molva* : Atlantic Salmon, *S. salar* : Grey Seal, *H. grypus* : Plaice, *P. platessa* : Pollack, *P. pollachius;* Poor Cod, *T. minutes;* Saithe, *P. virens* and Whiting, *M. merlangus.*Data on occurrences of these species were processed using polygon refinement and HSSD and the individual species layers developed were combined by overlay addition to create the final sub-model.

5.4 Overall Model Development

The five sub-models were combined using a multi-criterion evaluation (MCE) weighted in terms of any potential detrimental impact created by aquaculture development (Fig. 5.2). The weightings used (Table 5.1) were developed by a range of ten experts that provided information on which factors they felt where most important when considering aquaculture and its interacting with biodiversity indicators. Species Sensitive to Aquaculture and Endangered Species sub-models were weighted higher as they are deemed to be the most critical in terms of the effect aquaculture activities would have upon them. The resulting consistency ratio of the MCE matrix was 0.03, well within the range considered acceptable.

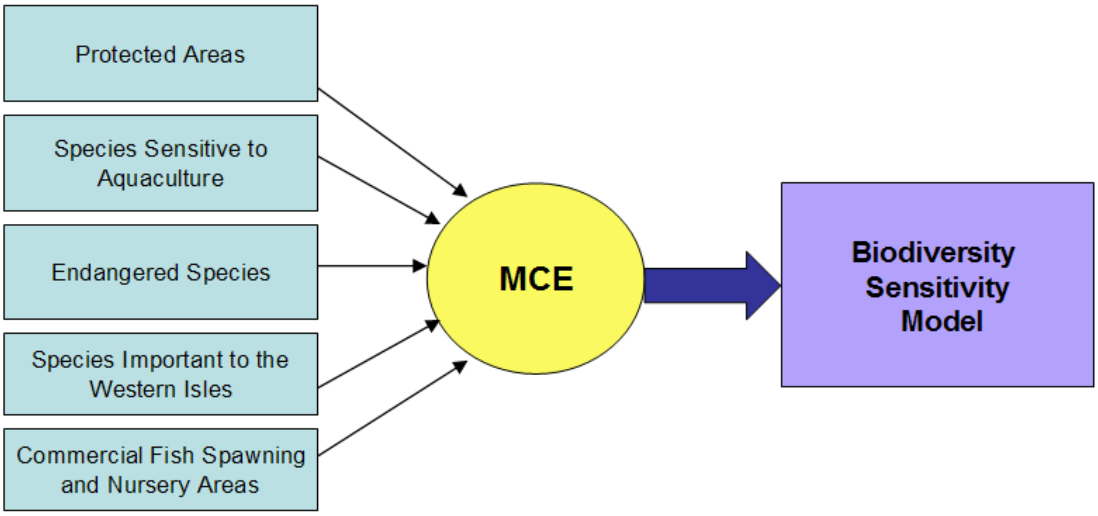

Fig. 5.2 Conceptual structure of the biodiversity sensitivity model for the Western Isles using five biodiversity indicator sub-models.

Table 5.1 Weightings for each of the five sub-models used in the final biodiversity model for Western Isles aquaculture.

Sub-model	**Weighting**
HSSD sub-model Species Sensitive to Aquaculture	0.3621
HSSD sub-model Endangered Species	0.3621
Fisheries Spawning and Nursery areas	0.1067
HSSD sub-model for Species important to the Western Isles	0.1067
Protected Areas	0.0389

5.5 Results

Protected Areas Sub-model:

Combining all the legislated protected areas for the Western Isles through the GIS (Fig. 5.3) shows that on land there are numerous overlapping designations of protection located in North Harris, North Uist and South Uist. Protected areas in the coastal zone are principally located in North and South Harris. The southernmost Isle of Barra has only two protected designations on Barra head. Significantly this model indicates that there are currently very few marine environmental protected areas around the Western Isles.

HSSD sub-model for Species sensitive to aquaculture:

The areas with highest numbers of sensitive species are found in North Uist, Benbecula, South Uist, and Loch Roag (Fig. 5.4) in sheltered locations. These sheltered locations provide the particular physio-chemical conditions essential for the formation of Maerl beds (Barbera *et al*., 2003). Those areas with the lowest number of species sensitive to aquaculture were south of Barra, North of Lewis and an area near Scalpay.

HSSD sub-model for Endangered species:

The HSSD sub-model of endangered (red-list) species (Fig 5.5) indicates that the areas on the isles of Lewis of Loch Roag, Loch Erisort Loch Leurbost and Stornoway have the highest numbers of endangered species. In comparison, the areas with lowest numbers of endangered species were mainly around South Uist, Barra and the north of Lewis. Some areas of Lewis have the highest rankings of endangered species, due to the presence of more than one endangered species in the same area.

Commercially important fish spawning and nursery areas sub-model:

Combining layers of known spawning and nursery areas for a range of commercially important fish species indicated the North Minch area to be highly important for spawning and nursery grounds, giving scores of higher sensitive areas in particular near to the east coast of the Isle of Lewis (Fig 5.6). Also in particular, Loch Seaforth, Loch Erisort and Loch Leurbost were shown as priority conservation areas having ten of the twelve identified commercially important species. This layer indicates that Loch Seaforth, Loch Erisort and the North Minch are highly diverse areas for commercial fish spawning and nursery areas, while the areas of Barra and South Uist are indicated as low levels of spawning/nursery grounds for commercial fish.

HSSD sub-model for Species important for the Western Isles:

The highest numbers of species important for the Western Isles were located in Loch Roag and from South Uist to Benbecula where the Grey and Common Seals have the greatest influence on the results (Fig 5.7). The areas of lowest diversity were south of Barra and some sites along the eastern coast of Lewis. Loch Roag, East Loch Tarbert, Sound of Harris, Benbecula and the sound of Barra all have high rankings of important general species.

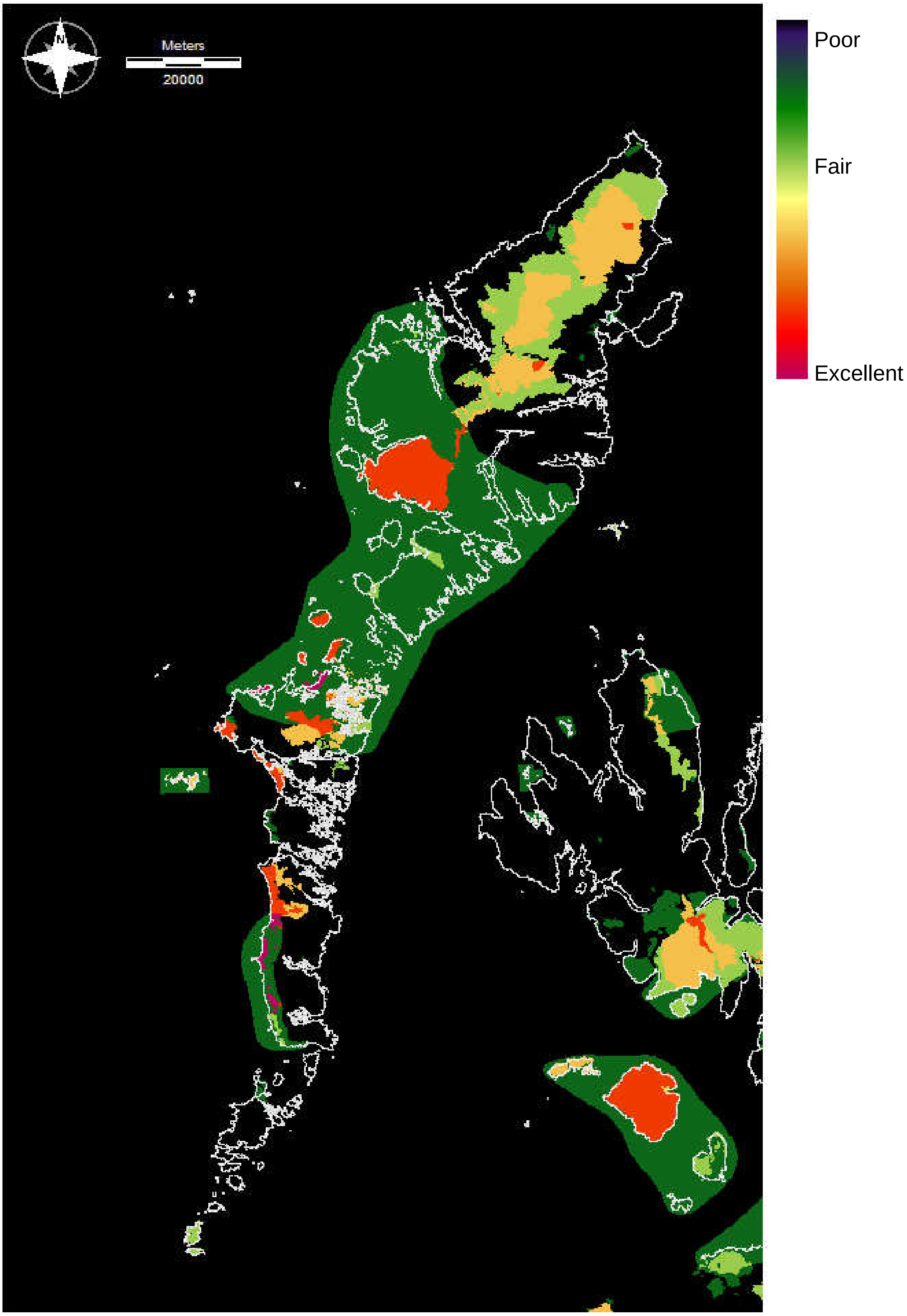

Fig. 5.3 Sub-model outcome showing the overlaid designated protected Areas in the Western Isles.

The legend represents the actual legislative protected areas and associated coverage rankings on a continuous scale from poor to excellent.

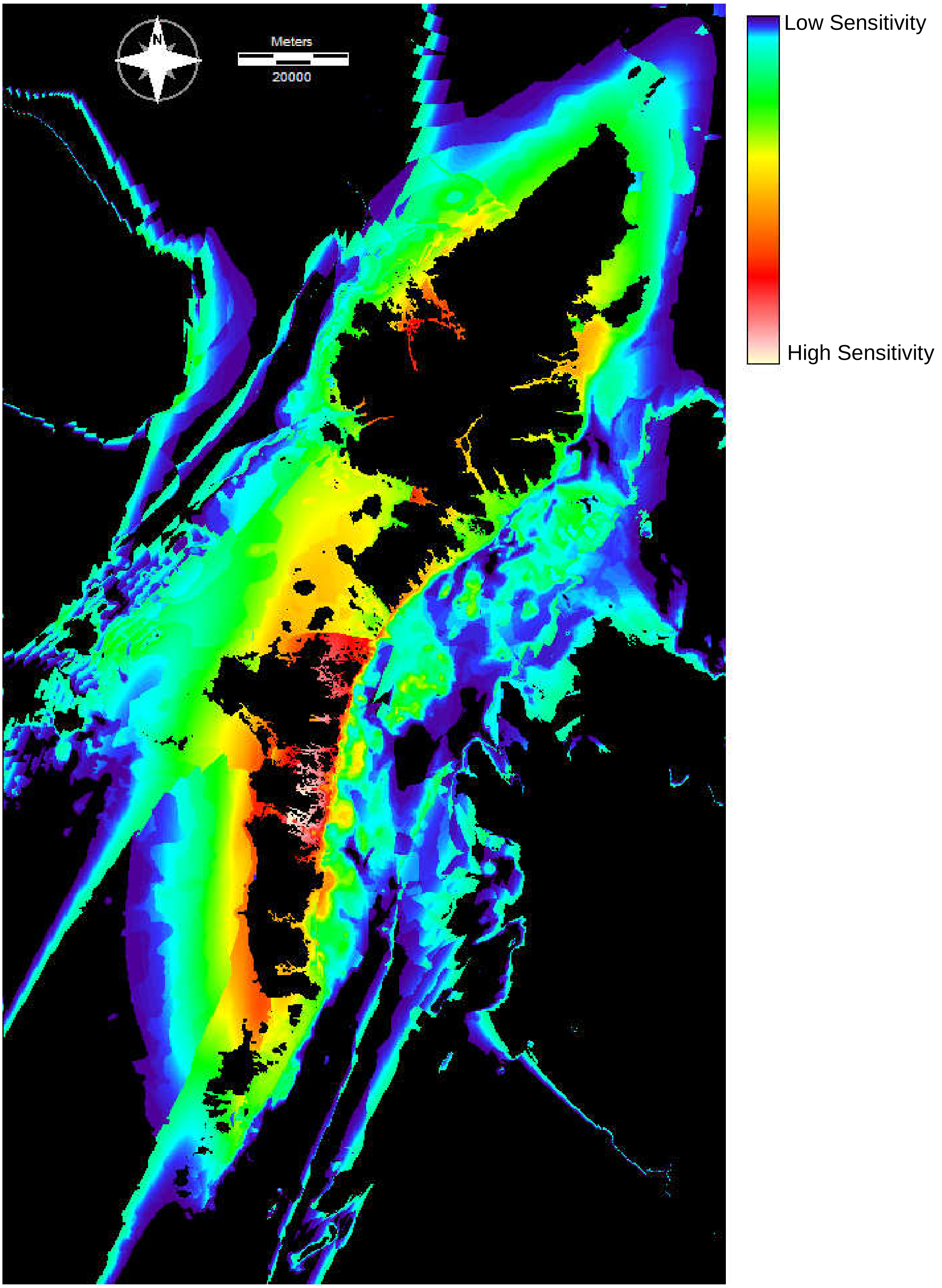

Fig. 5.4. HSSD Sub-model outcome showing distribution of species sensitive to aquaculture in the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

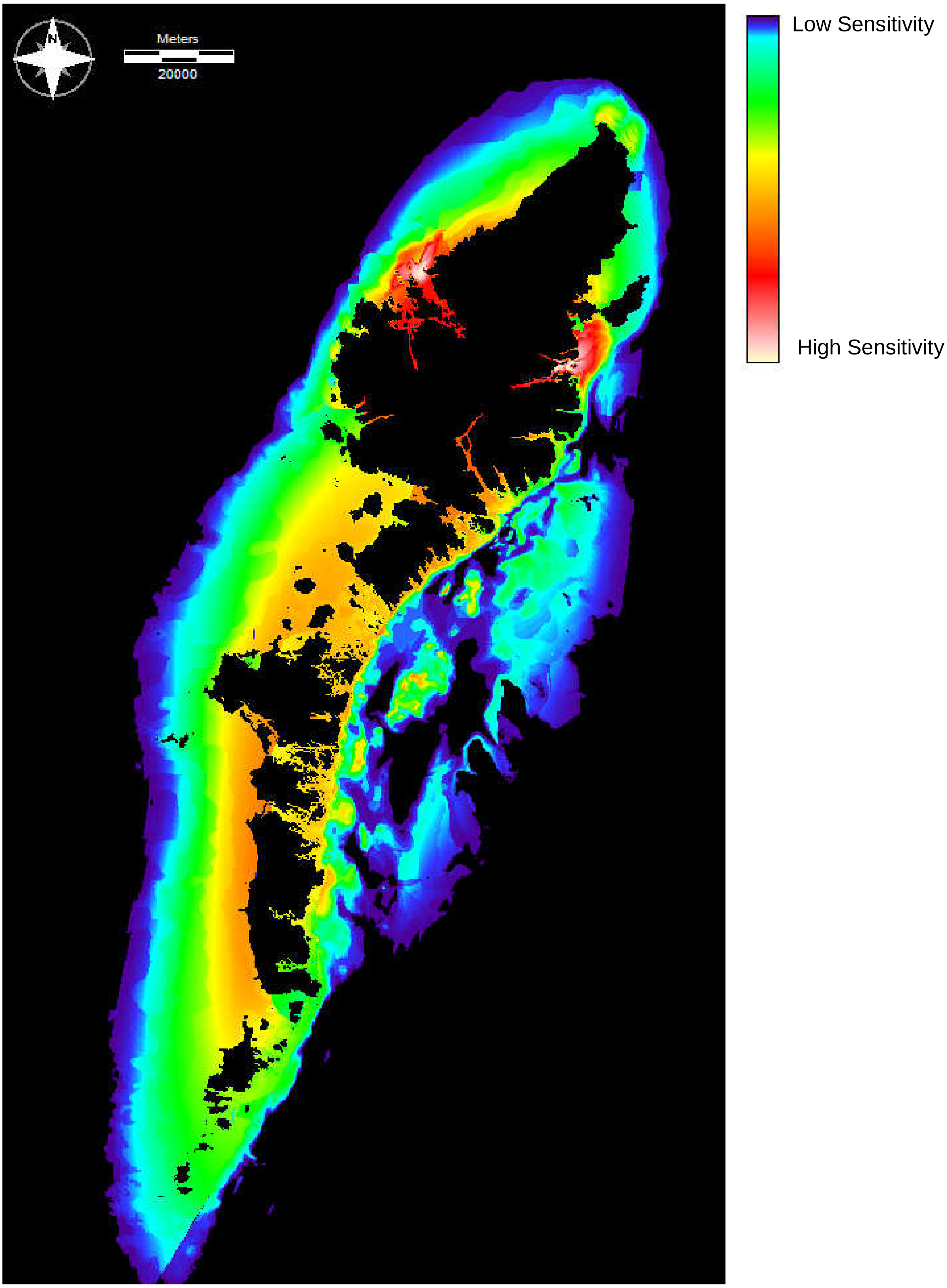

Fig. 5.5 HSSD Sub-model outcome showing distribution of Endangered Species in the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

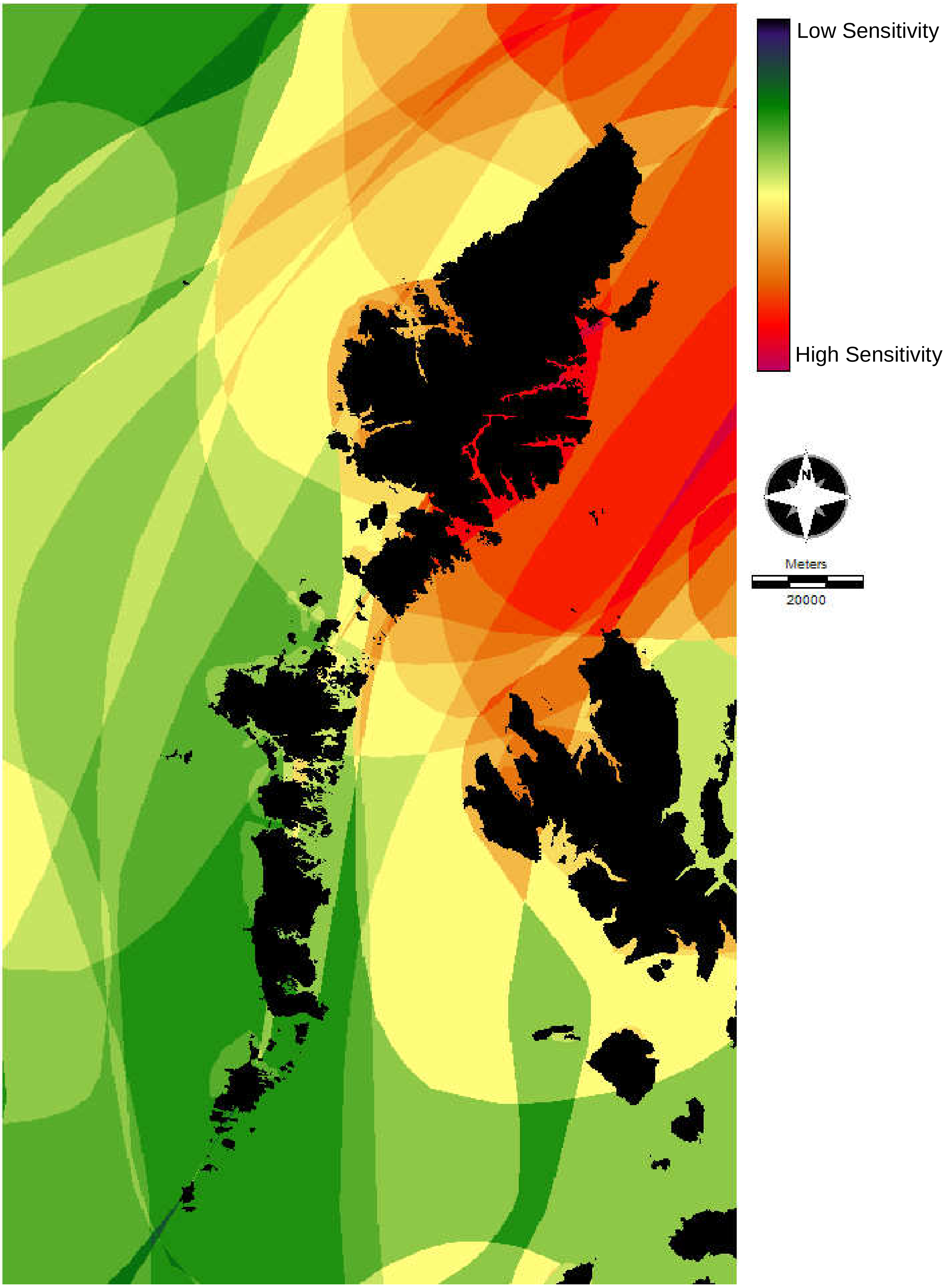

Fig. 5.6 Sub-model outcome showing cumulative distribution of fourteen important commercial fisheries species around the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

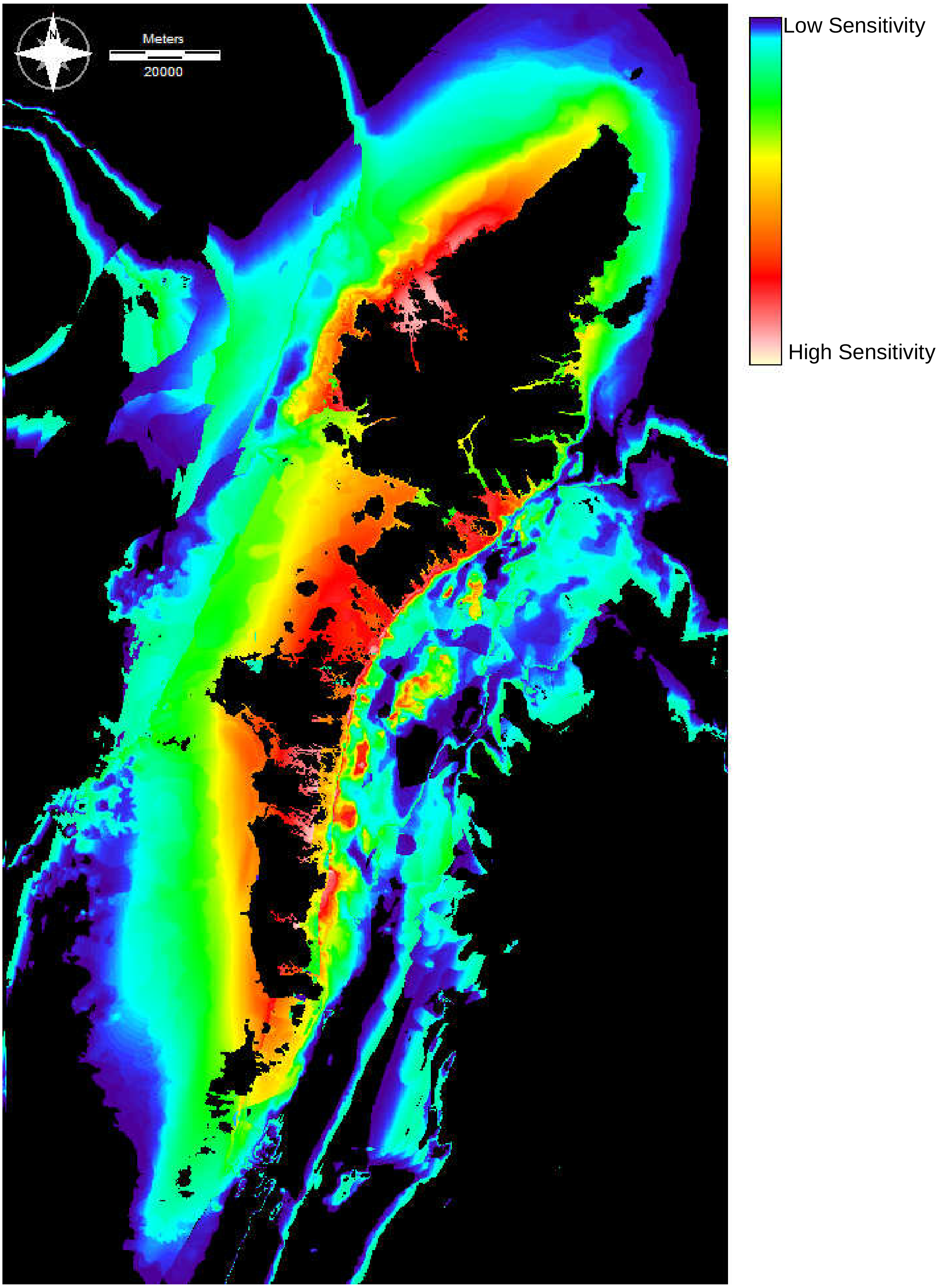

Fig.5.7. HSSD Sub-model outcome showing the distribution of species important to the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

Final biodiversity sensitivity model:

The final biodiversity sensitivity model combining the five sub-models using MCE indicates that 1168km^2 around the Western Isles (4% of the total study area) has highly sensitive biodiversity in relation to aquaculture (Fig. 5.8). By contrast, 20595km^2 (65% of study area) has biodiversity which has a relatively low sensitivity to aquaculture. All thresholds were determined by the author. The model confirms areas previously known to have a high overall biodiversity sensitivity, such as in Loch Roag and the north-east of North Uist, (Malthus *et al*, 2006), but also highlights other areas which were not previously considered such as the east coast of Benbecula.This provides clear indications of those areas which are sensitive to aquaculture development in the Western Isles and many of these areas are known to be important for present and future development of aquaculture. Table 5.2 shows the areas identified for each sensitivity ranking.

Table 5.2 Area results for final biodiversity sensitivity model in km^2

Colour	**Relative Sensitivity**	**Category Area (km^2)**
Black		5170
Dark Blue	Low	20595
Dark Green		2203
Moderate Green		930
Light Green		709
Yellow		825
Light Orange		479
Dark Orange		337
Light Red		243
Dark Red		78
Burgundy	High	31

Aquaculture and Sensitivity Biodiversity Model Comparison:

Further exploration of the interactions between current activity fish farms and the predicted biodiversity sensitivity areas was carried out By overlaying the locations of present aquaculture farms onto the Biodiversity sensitivity model. It is clear that currently there are many successful farms which are located within areas that are predicted to be highly sensitive to aquaculture (Fig. 5.9).

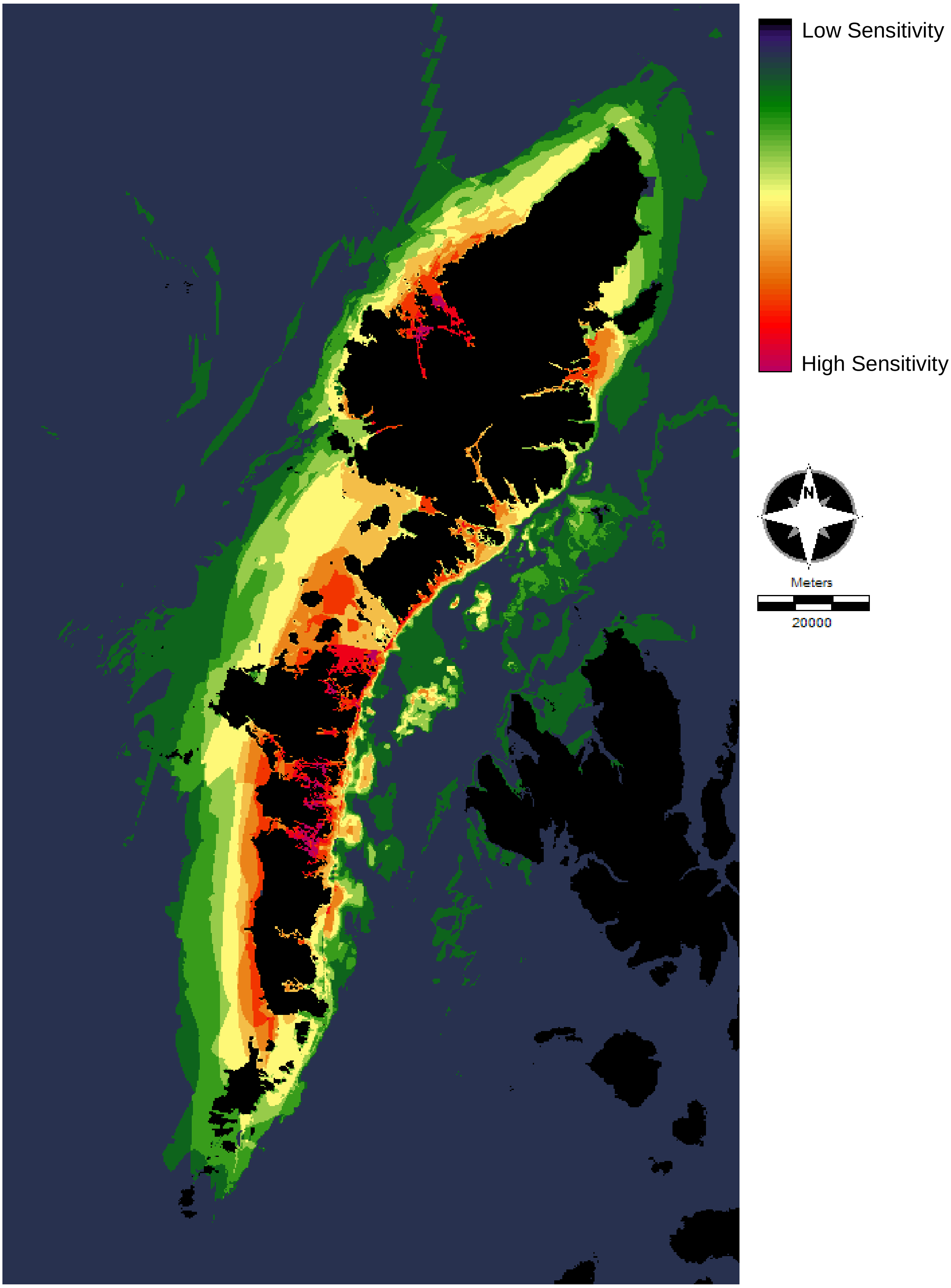

Fig. 5.8. Overall model of Biodiversity sensitivity to aquaculture for the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

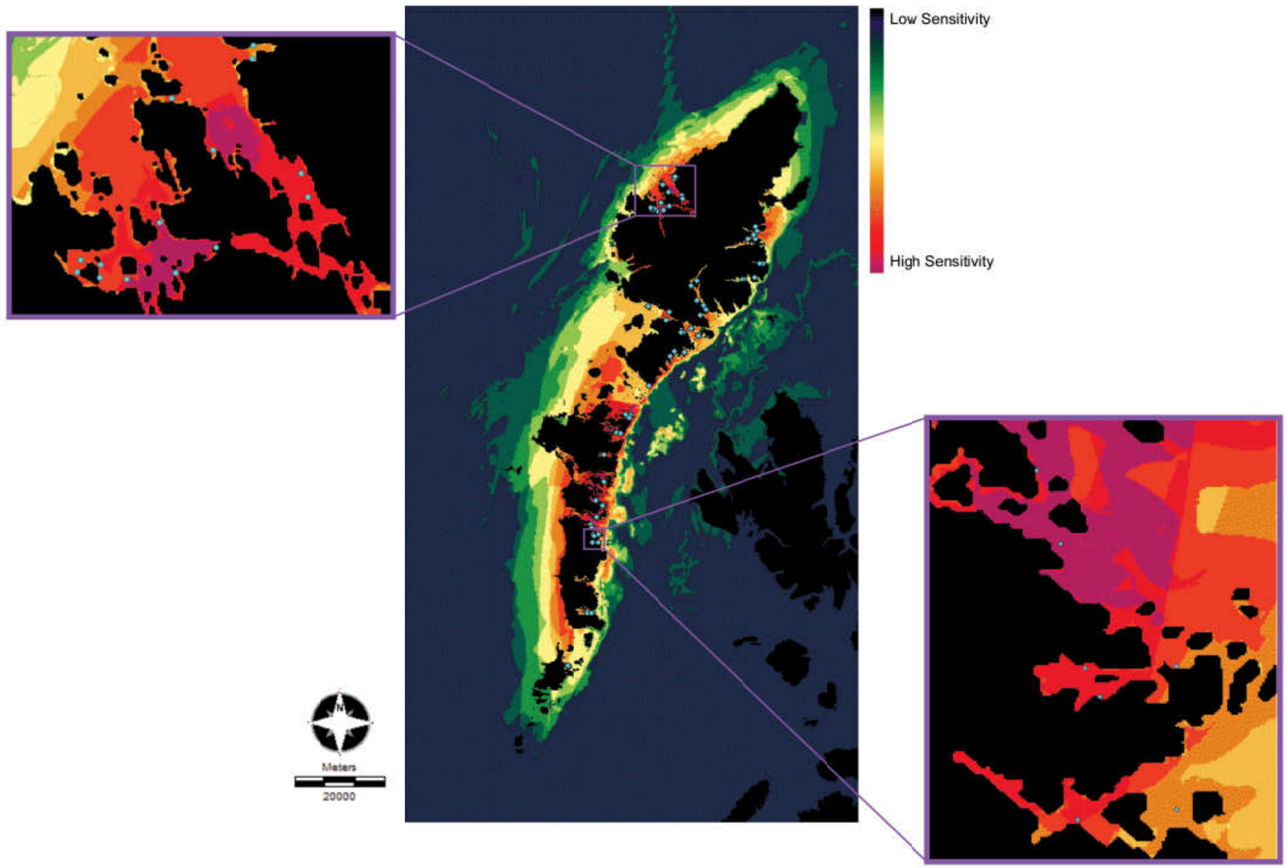

Fig. 5.9 Current active fish farm locations in the Western Isles (indicated as cyan dots) overlaid on the Overall model of Biodiversity sensitivity to aquaculture for the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

5.6 Discussion

The Biodiversity sensitivity model developed here using biodiversity indicators can be used to assess the ability of coastal sites to incorporate aquaculture activities whilst still ensuring that the relevant biological criteria such as species sensitivity for important species, sensitive species and environments, and fishery nurseries and spawning areas are considered. Current methods for assessing and delivering information on Biodiversity in Scotland are complex, incoherent and almost certainly not cost effective (Hambrey Consulting 2008). As such, currently there is no clear definition of which variables are needed to represent biodiversity when considering aquaculture development. Biodiversity indicators can be used for the measurement of structure, composition, or function of the ecosystems, the indicators can be considered through individual species and habitats assessments (Niemi and McDonald, 2004) this type of assessment strategy are strong indicative tools for identifying in a concise coherent manner the important biodiversity areas. The model developed here is based solely on considering aquaculture development and as such determines the aspects of biodiversity indicators and their sensitivity to aquaculture development in the Western Isles. This type of biodiversity indicator assessment is an approach which encourages stakeholder engagement, is practical in its application and presents complex information in a logical manner. This gives a more extensive GIS framework for coastal zone management of sustainable aquaculture. The biodiversity sensitivity model developed here can be a stand alone tool or incorporated into a large holistic model for aquaculture. It has been defined through a set of procedures in a macro model for HSSD sub-models and the combining of those sub-models that are standardized and easily adapted as needed. Where this model is innovative is its approach to the combination of species and groups of indicator species. Current species distribution and habitat assessments are focused upon individual species and do not consider management of a group level. Species distribution models are important for any marine management strategy (Guisan and Thuiller, 2005; Degraer *et al*., 2008) the model present here shows how these models can be developed in a manner that is relevant for the coastal development under study (Aquaculture).

The representation of these aspects in a spatial database illustrates areas, which are indicated as high and low biodiversity sensitivity for the study area. The areas with high diversity for the Western Isles need thorough in-depth investigations into the likely impact any development would have and to minimize potential conflicts. This model is highly advantageous in aiding management decisions and conveying results to all stakeholders. Vital to the successful application of any GIS model is ensuring the relevant stakeholders, including the wider public are fully involved (Pomeroy and Douvere, 2008).

GIS is a useful tool in measuring biodiversity as it allows different aspects to be combined and a representation of the biodiversity sensitivity of the Western Isles to be produced. The modelling of the biodiversity sensitivity of an area and the determination of the aquaculture development that may occur in these areas can identify if conflicts may arise. This framework is a proactive and adaptive management strategy that allows for the effective integration and use of new information, legislation and is capable of wholly integrating all parties in the decision making processes.

The areas with highest combined biodiversity according to this model, based on the factors included, were Loch Roag, Loch Maddy and Benbecula and Wiay. The areas shown to have least diversity are Barra and North Lewis. The low diversity present for Northern Lewis can be attributed to low species counts in this area, which will directly impact on endangered and sensitive species present in this area.

Two of the most recent biodiversity studies of the Western Isles: one by Malthus et al, 2006 carry out extensive biological surveys of the sound of Harris with the overall aim of producing a comprehensive biotope map of the Sound. The second one by Harris et al, 2007 undertook biotope mapping of the Sound of Barra, where they combined acoustic and optical approach exploiting synergies in the two techniques allowing discrimination of biotopes. These surveys' both implement a range of methods for assessment such as satellite imaging, acoustic survey and extensive ground truthing. The surveyed sites of the sound of Harris and sound of Barra considered in Malthus et al 2006 and Harris et al 2007 both identified that these sounds are likely to be considered sensitive sites when there is a detrimental impact on the hydrological conditions which is consistent with the findings of this study and a previous study by Wilding et al, 2005. The benefit of the GIS framework presented in this study is it is capable of presenting valid results, in a streamlined approach and can identify areas that would benefit from a site survey without having to carry out extensive initial surveys.

Prospective sites for placement of aquaculture:

To determine the best areas to place aquaculture in relation to biodiversity for the area of the Western Isles all the factors have to be considered. The models are the best representation of the accumulation of the important species and habitats in relation aquaculture development. Loch Roag, Sound of Harris, Loch Maddy and Eastern coast of Benbecula are indicated to have the highest diversity according to this model. This is an interesting point as the area with the most aquaculture sites already established for the Western Isles is Loch Roag (WIAA, 2005). Areas of low diversity are present around the coast of Barra, Northern Lewis and some scattered areas around the coast South Uist. Areas that are indicated as high biodiversity should be need full investigated and assessed when considering any aquaculture development.

Distribution of established aquaculture sites:

There is a clear correlation between areas of high biodiversity and aquaculture sites. This correlation needs further study to determine the relationship if there is one that is occurring within these areas. Interestingly the biodiversity sensitive species identified are not associated with anthropogenic contamination and the increase in biodiversity is not concerned with nutrient enrichment which has been previously identified as the reason for high biodiversity near fish farms and sewage outlets (Pastorok and Bilyard, 1985; Hillebrand *et al*., 2007). This could be coincidence, i.e. high biodiversity exists mostly in sheltered areas where aquaculture is common. There is also a definite decrease in the number of aquaculture sites as the score of biodiversity decreases i.e. the areas with least biodiversity have apparently less aquaculture sites present. This may be explained in a number of ways:

- There are many regulations surrounding aquaculture thus knowledge of the biodiversity in regions where aquaculture is present is increased. This could result in the increase of biodiversity shown to be present in these areas.
- Conditions that are favorable for the placement of aquaculture may also enhance biodiversity i.e. sheltered conditions, conversely more exposed open coast conditions are less conducive to locating aquaculture on having high biodiversity due to the dynamic environmental conditions
- Aquaculture may actually increase the biodiversity of a wider area. This contradicts much of the perceived wisdom on biodiversity and aquaculture,

though this is normally considered within the zone of impact around the fish cages.

Biodiversity measurements in Scotland have evolved and adapted with little consideration of design (Hambrey Consulting 2008) and given the increasing momentum for a change in the way marine waters are managed in Scotland (Baxter *et al*, 2008), there is a need for the modeling of biodiversity in a coherent and understandable manner and predictive modeling techniques of species and important habitats are ideally suited for such a problem (Maxwell *et al*, 2009). The drive behind any final structure to assess biodiversity is it must deliver three key outcome objectives of the Scottish Biodiversity Strategy: specific action for species and habitats; higher level action for landscapes and ecosystems and engagement of people in the management and enjoyment of biodiversity (Hambrey Consulting 2008) as shown in this study GIS is capable of delivering such key outcomes in a consistent and strategic manner.

In conclusion, the distribution of biodiversity for the area of the Western Isles needs to include a combination of aspects, which have to be considered in relation to sustainable aquaculture development. The development of a biodiversity sensitivity model for Western Isles is replicable for the rest of Scotland and defines a framework that can explore alternative scenarios. This allows aquaculture development to identify what conflicts and compatibilities their management plans will have on biodiversity sensitivity of the Western Isles.

5.7 References

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5.8 Appendix: Supplementary figures.

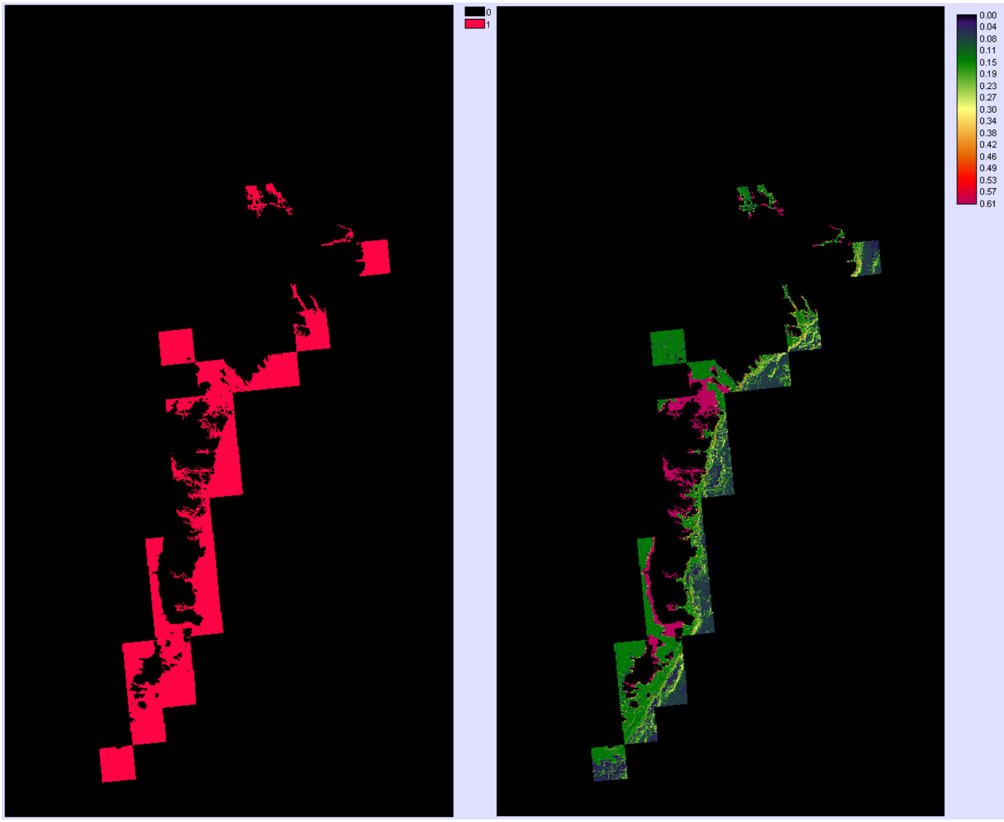
Appendix A: Addition information on extracting species information.

A formula in excel was developed for this purpose and is illustrated in Appendix 2. The species in Row 1 column B is compared to all species contained in column A using the formula present in column C row 1. Every row in column C provides the same function for its equivalent row in column B. When the formula auditing mode in excel is changed (by pressing Ctrl +`) Column C will change to either true or false depending upon if the species name is present in column A. An example of this is shown in figure 2 where column C says false except for row 4; this is due to the fact that the species name in column B of row 4 is present in column A (row 8). The use of this formula in excel means that a list can rapidly compared for similarities against other lists.. A formula in excel was developed for this purpose and is illustrated in Appendix 2.The species in Row 1 column B is compared to all species contained in column A using the formula present in column C row 1. Every row in column C provides the same function for its equivalent row in column B. When the formula auditing mode in excel is changed (by pressing Ctrl +`) Column C will change to either true or false depending upon if the species name is present in column A. An example of this is shown in figure 2 where column C says false except for row 4; this is due to the fact that the species name in column B of row 4 is present in column A (row 8). The use of this formula in excel means that a list can rapidly compared for similarities against other lists.

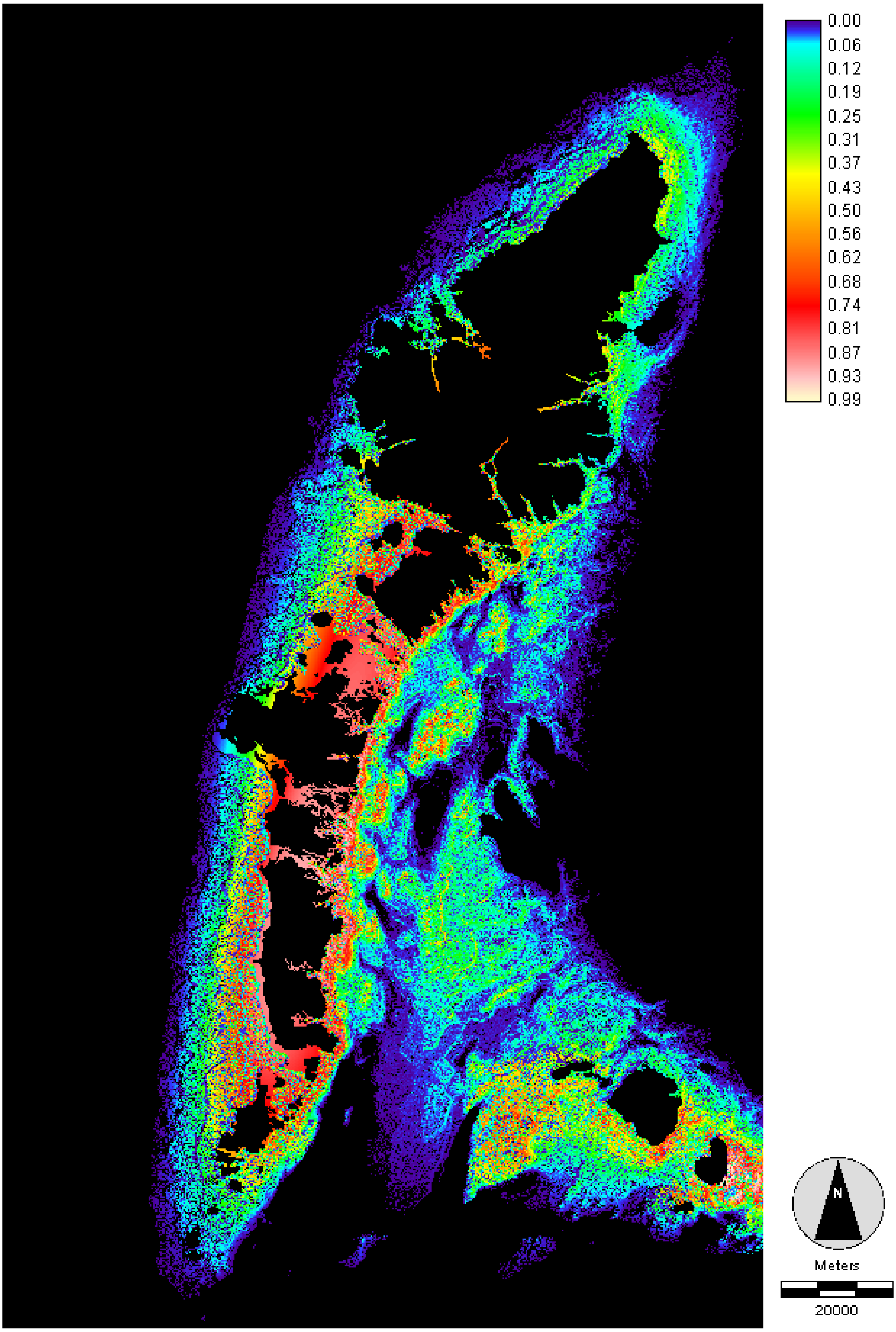
The list of endangered species in the United Kingdom was compared in this way for each of the species lists received from the NBN gateway. Once the formula is created for the list of endangered species each of the species lists can be copied and pasted into column A and the results read from column C. Considering that some of the species lists are over 2000 names long this formula was used to speed up the process of identifying endangered species.

The vector layers were initially created in UKGRID format as vector polygon files. The UKGRID coordinates of each corner point of the 10km squares were used to construct the vector polygons. UKGRID was not a recognized reference file in the IDRISI however it has the capability to create files that are appropriate for each study. The UKGRID reference was created with the following information (See figure A3). Ensuring that the initial layers created were georefence corrected was critical for calculations to reproject to UTM29n ensuring all models matched. To create polygon vector layers a vector export file (*.VXP) was manufactured in Idrisi text editor.

A1: Representative species presence polygon map on left and resulting confidence map on right.



A2: Final Representative HSSD output for the common seal



A3: Reference file created for UKGRID

ref. system : UK Grid
projection : Transverse mercator
datum : delta WGS84
: 384 -111 425
ellipsoid :
major s-ax : 6377563.396
minor s-ax : 6356256.900
origin long : -2
origin lat : 49
origin X : 400000
origin Y : -100000
scale fac : 0.999601272
units : m
parameters : 0_

A4: Example of a vector export file with only one polygon feature, created in IDRISI text editor.

Vector Layer Name : Acipenser sturio
Vector Layer Type : Polygon
Reference System : latlong
Reference Units : deg
Unit Distance : 1.0
ID/Value type : Integer
Number of Features : 1

Feature Number : 1
ID or Value : 1
Minimum X : -6.298452
Maximum X : -6.116607
Minimum Y : 58.456440
Maximum Y : 58.551617
Number of Parts : 1

Part Number : 1

Number of Vertices : 5

Coordinates (X, Y) : -6.2875 58.4564

:-6.2984 58.5459

:-6.1271 58.5516

: -6.1166 58.4620

: -6.2875 58.4564

A5: Example of the formula used in excel to check for presence of endangered species in the NBN gateway lists.

Row	Column A	Column B	Column C
1	*Nebria gyllenhali*	*Acipenser sturio*	=OR(EXACT(F6,A1:A2000))
2	*Nebria salina*	*Acrocephalus paludicola*	=OR(EXACT(F7,A1:A2001))
3	*Notiophilus biguttatus*	*Alopias vulpinus*	=OR(EXACT(F8,A1:A2002))
4	*Loricera pilicornis*	*Alosa alosa*	=OR(EXACT(F9,A1:A2003))
5	*Pterostichus adstrictus*	*Alosa fallax*	=OR(EXACT(F10,A1:A2004))
6	*Pterostichus niger*	*Anergates atratulus*	=OR(EXACT(F11,A1:A2005))
7	*Calathus fuscipes*	*Anser erythropus*	=OR(EXACT(F12,A1:A2006))
8	*Alosa alosa*	*Apristurus aphyodes*	=OR(EXACT(F13,A1:A2007))
9	*Fulmarus glacialis*	*Aquila clanga*	=OR(EXACT(F14,A1:A2008))
10	*Fratercula arctica*	*Austropotamobius pallipes*	=OR(EXACT(F15,A1:A2009))
11	*Larus marinus*	*Aythya nyroca*	=OR(EXACT(F16,A1:A2010))

A6: Example of results derived from application of the formula shown in A5.

	Column A	**Column B**	**Column C**
Row 1	*Nebria gyllenhali*	*Acipenser sturio*	FALSE
Row 2	*Nebria salina*	*Acrocephalus paludicola*	FALSE
Row 3	*Notiophilus biguttatus*	*Alopias vulpinus*	FALSE
Row 4	*Loricera pilicornis*	*Alosa alosa*	TRUE
Row 5	*Pterostichus adstrictus*	*Alosa fallax*	FALSE
Row 6	*Pterostichus niger*	*Anergates atratulus*	FALSE
Row 7	*Calathus fuscipes*	*Anser erythropus*	FALSE
Row 8	*Alosa alosa*	*Apristurus aphyodes*	FALSE
Row 9	*Fulmarus glacialis*	*Aquila clanga*	FALSE
Row 10	*Fratercula arctica*	*Austropotamobius pallipes*	FALSE
Row 11	*Larus marinus*	*Aythya nyroca*	FALSE

Chapter 6

A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Visual, Seascape and Landscape Capacity analysis to support marine cage aquaculture site selection.

Donna-Claire Hunter, Trevor C Telfer and Lindsay G Ross.

This chapter describes the application of GIS as an analytical approach for the improvement of aquaculture resource management to identify appropriate site locations on the Western Isles in terms of visual impact of the cages.

An Appendix section of additional supporting figures has been included. This information is not in the body of the text as it does not constitute part of a manuscript which is to be submitted as a journal article but has been included as it aids understanding of the chapter.

The main author, D-C Hunter, is responsible for the development of the spatial models. Lindsay G Ross and Trevor C Telfer provided supervisory and editorial support.

This manuscript will be submitted to *Environmental Modelling and Software*.

Visual, Seascape and Landscape Capacity analysis to support marine cage aquaculture site selection.

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Abstract

This paper presents a GIS approach to determining the level of the impact of aquaculture development on the scenic surroundings of the Western Isles, Scotland. This is based on combining the two main areas of landscape capacities and seascape sensitivities. The study explores landscape and seascape character assessments and explores how to refine them to represent sensitivity and capacity scores for aquaculture development. Visibility analysis is based on proportional viewsheds from a range of key visual receptors. These sub-models are then combined through overlay and multi criteria evaluation to develop a final Western Isles Visual Capacity model. The model outcomes show that the Western Isles has substantial further capacity for aquaculture development in terms of potential visual impact. The final model indicates that the Western Isles has 1324km^2 (4% of study area) where there is low capacity for new aquaculture development structures. While 3301km^2 (10% of study area) has a moderate capacity to incorporate new aquaculture structures. Lastly 6448km^2 (20% of study area) is categorized as having a high capacity to incorporate new aquaculture developments. Overall there is potential for aquaculture to continue to develop on the Western Isles with minimal impact on the scenic beauty.

Keywords: Visual, Landscape, Seascape, GIS modeling, Aquaculture.

6.1. Introduction

On-shore and offshore aquaculture activities have varying visual impacts on landscape, and seascape quality. In recent years visual impacts have been widely publicized in comparison with the other environmental issues, and have become a contentious issue (The Buteman, 2009). Shang and Bishop (2000) studied the relationship of the aesthetic appeal of landscapes and the visual impact of objects within the landscape in relation to their size, contrast and shape. However, there still is no objective method to set a threshold for the perceived adverse visual impacts of objects (Mouflis *et al*, 2008).

Under the guidelines set out by the Landscape Institute and Institute of Environmental Management and Assessment (2002), to fully assess landscape sensitivity it is necessary to assess the visual effects of aquaculture development. To assess visual impacts the existing main techniques currently involves mapping of zones of visual influence, visual envelopes or visual corridors. These are most often hand-drawn on to maps with annotations defining the important characteristics and highlighting possible changes that would occur if a development were to proceed. The information provided in a visual analysis indicates the likely numbers of public receptors which can be wide ranging groups such as tourists or locals, the significance of the view, and the likely sensitivity of the receptors. The significance of the view is defined by the proportion of the visual receptors within the study area which are likely to experience the new structures. These methods are time consuming and usually carried out by specialist landscape architects. Photomontages are employed to help visualize changes and to examine methods to reduce adverse visual impacts.

Bishop and Hull (1991) identified five basic functions, which are important in creating a concise visual assessment - clear identification of the various types of impacts; organization of spatially and temporally dispersed inventory data; prediction of impacts based upon potential land use decisions; a usable interface between these functions and the planner/manager; effective communication of potential impacts to the public and decision-makers. These functions are further complemented by guidelines set by the Countryside Agency and Scottish Natural Heritage (2002). When assessing seascapes, specific guidance can be found in only a few studies, including the Countryside Council for Wales, (2001) and Grant (2006). The importance in determining seascape characters has recently been raised in other

countries such as New Zealand for aquaculture planning (Rennie *et al*, 2009) and marine spatial planning in Ireland (Flannery and Cinnéide, 2008),
The visual analysis incorporated in this study is based on a viewshed approach (Kim *et al*, 2004) which is a widely used technique in GIS (O'Sullivan and Turner, 2001). Successful implementation of viewshed techniques can be seen in a range of diverse studies such as determining visual impact of quarries (Mouflis *et al*, 2008), evaluating environmental amenities, particularly views and open space access and the impact this has on residential home sales (Sander and Polsky, 2009), optimal path route planning (Lee and Stucky, 1998), wind turbines placement (Benson *et al*, 2004), (Devereux *et al*., 2008) and archaeological visualization (Wheatley and Gillings, 2000).

This study focuses on visual impact assessment for coastal finfish farming, an activity which involves both land and offshore based structures. The approach is to develop GIS-based analysis of landscape value, visual sensitivity, landscape sensitivity and seascape sensitivity, from which to create a final visual landscape capacity sub-model. The overall aim is to develop a GIS-based model for the objective analysis of visual risk with a view to minimizing negative visual impacts on the wider environment.

6.2 The Study Area

The chosen study area for this research was the Western Isles, which is renowned for its stunning combination of striking landscapes with an elemental beauty (http://guide.visitscotland.com/). Just off the North West coast of Scotland, (Fig.6.1), the Isles are currently home to an extensive aquaculture industry, which has significant potential for future growth. The five main islands of the group, Lewis, Harris, North Uist, Benbecula, South Uist and Barra, have a combined coastline length of 2,103km.

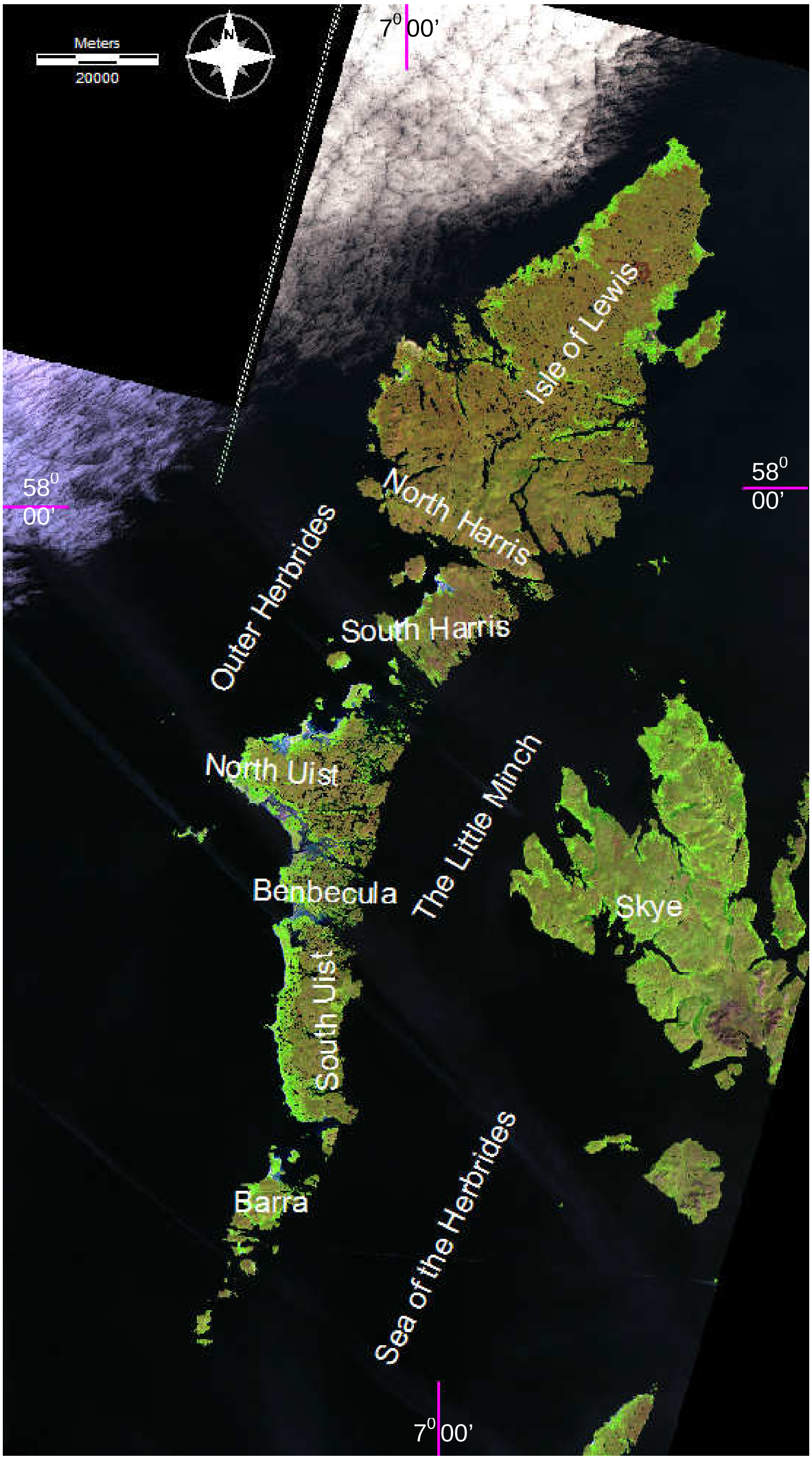

Fig.6.1 The Western Isles off the North West coast of Scotland.

6.3. Model components and Development

The visual assessment model consisted of three major components, landscape value, visual assessment (viewshed) and landscape sensitivity or character. All the model components were developed in the IDRISI Andes GIS system (Clark Labs) and all layers were georeferenced to UTM-29N and have a spatial resolution of 30m.

6.3.1 Landscape value sub-model

Landscape values are ratings assigned to those areas which are currently protected or designated as significant areas. They are considered to be a key component of any landscape assessment and are: *"… concerned with the relative value that is attached to different landscapes. In a policy context the usual basis for recognizing certain highly valued landscapes is through the application of a local or national landscape designation."* CA and SNH 2002.

Much of the Western Isles has been designated as a National Scenic Area (NSA) by the Scottish Government, and this is considered the most important criteria for landscape value as defined by current governing policies CA and SNH 2002. This "Landscape Value" model layer therefore consists of two areas; one within and one out with the designated NSAs. In addition, an intermediate visual buffer zone is incorporated within the model as a third zone. As there is no conformity on what distance this buffer zone should be, a 5 km visual envelope has been used to allow consistency with the "Visual Sensitivity" sub-model. The "Landscape Values" model layer is shown in Fig. 6.2.

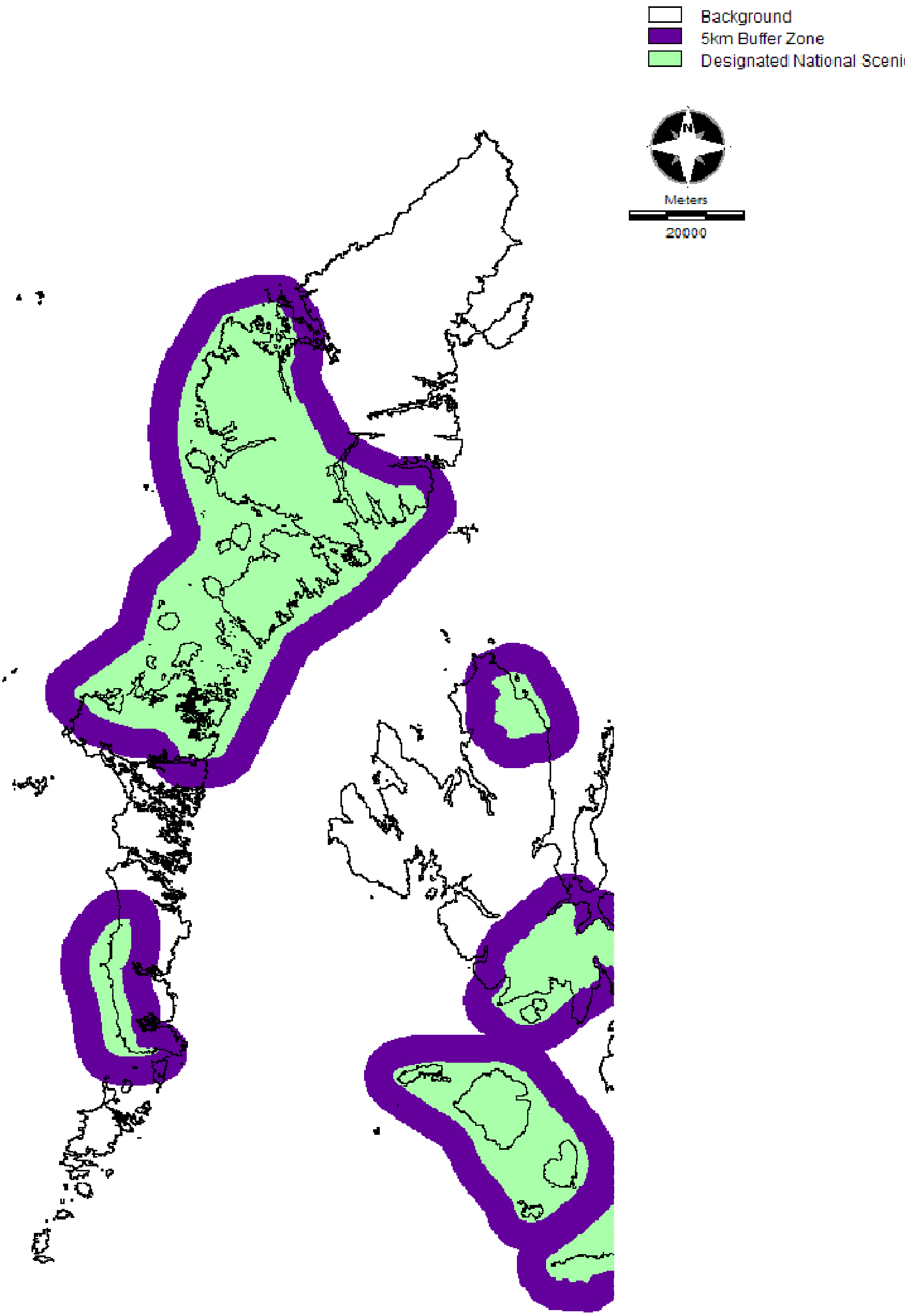

Fig. 6.2 Landscape Value based on designated National Scenic Areas.

6.3.2 Visual Sensitivity Sub-model

Visual assessment of the Western Isles was developed within the GIS using the novel approach of proportional visual analysis. The IDRISI GIS method used for visual assessment employed a process known as Viewshed analysis which calculates intervisibility, in which the visibility between points by line of sight within a specified distance is assessed using a digital elevation model (DEM) and presented as a two dimensional spatial layer. The strengths of a viewshed analysis are that it is entirely objective and is able to account for the location, height and angle of view of a visual receptor.

Viewshed analysis provides for two output types; either a Boolean Viewshed Analysis which represents simply whether any image pixel can be seen from the viewpoints or not and where a value of 1 represents seen and 0 not seen, or, a Proportional Viewshed Analysis which assigns a value to a pixel equal to the proportion of viewpoint pixels from which the cell is visible. The latter was used for this study and the output ranged from a pixel seen from only 1 of 10 input viewpoint pixels having a value 0.1 while a pixel seen from all 10 input viewpoints will have the value 1.0.

The Viewshed module in IDRISI required data from two raster images, a surface DEM and a viewpoint image. The visual heights of the viewpoints were set at 2 m from the surface, representing the average height of any observer. This falls into current policy guidelines (Benson *et al*, 2004).

Digital Elevation Model

The DEM used for this study was Landform profile 1:10000 scale map taken from the Edina Digimap website (http://edina.ac.uk/digimap/). This provides height data as 5m vertical interval contours (+/- 1m accuracy). The vector lines in the downloaded maps in the form of UKGRID 10km squares had numerous small errors and could not be accurately connected and so the contours were first converted to points using the GENERALISATION module in IDRISI and the final DEM was created by interpolation (INTERPOL) (Fig 6.3).

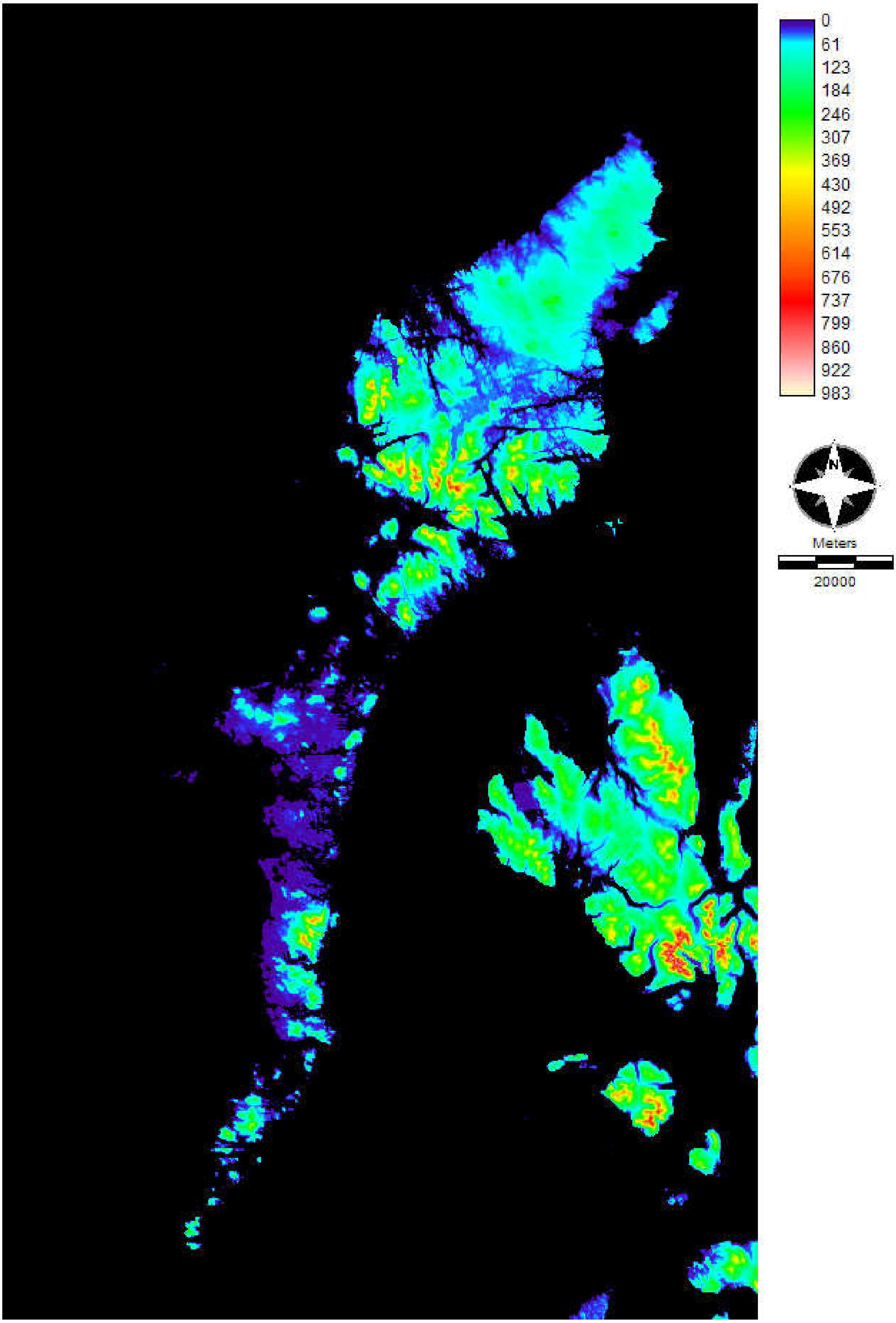

Fig.6.3 Digital Elevation model for the Western Isles, Scotland. Heights in metres.

View Source Images

Four main view source vector images were created and then combined to give the overall view source image. In the first, viewpoints were taken from a previous study of Benson *et al*, (2004). Here 47 ground-truthed points, representing a variety of important viewing areas from walks, popular view points, and dramatic coastlines were digitized. The second and third vector images contained roads and houses taken from the Ordnance Survey Land-Line from the Edina Digimap website (http://edina.ac.uk/digimap/). The fourth view source vector image was of ferry routes which are the main mode of transport for tourists and visitors to the Islands. These were digitized from routes shown on the Caladonian Macbrayne Ltd ferry timetable. All vector files were rasterized and combined for use in the Viewshed analysis. The final view source image is shown in Fig. 6.4.

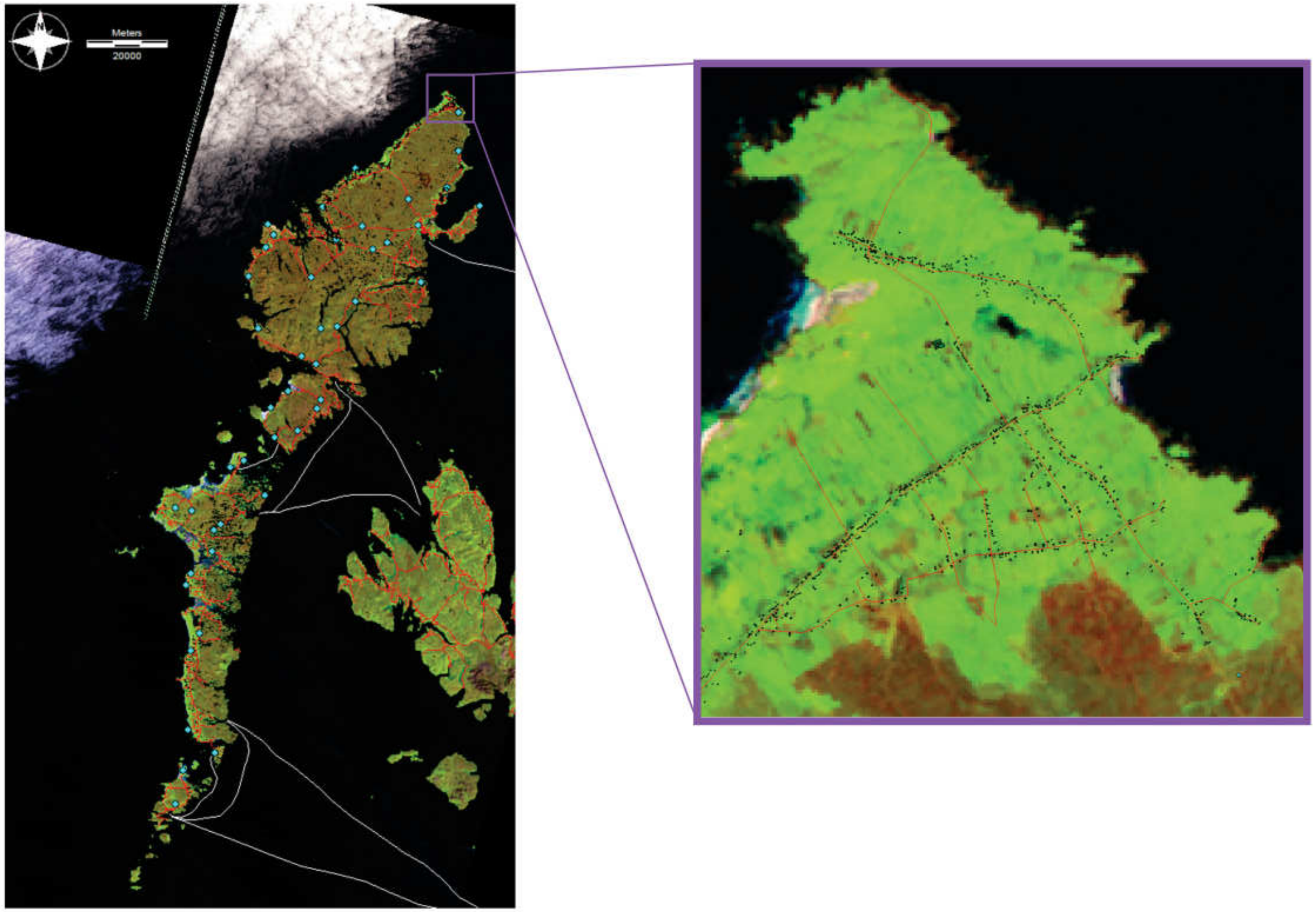

Fig. 6.4 Elements of the four view source images.

Houses (Blue polygons), Important viewpoints (Cyan dots), All Roads A, B, and Minor (Red) and Ferry Routes (White)

Viewshed analysis

The viewshed module can explore and quantify any defined visual envelope and the most appropriate envelope determined for this study was 5km. A proportional sub-model was developed, using the digital elevation model and the viewpoint source image (Fig. 6.5). This sub-model was further refined to give a qualitative overall visual sensitivity layer for aquaculture developments by reclassifying for categories based on the scheme adopted by Terence O'Rourke plc (Landscape Institute and Institute of Environmental Management and Assessment, 2002) and given in Table 6.1.

Table 6.1 Definition of magnitude/degrees of effects on visual amenity (Landscape Institute and Institute of Environmental Management and Assessment, 2002)

Sub-model Proportional View Scale	Reclassified Sensitivity Value	Impact	Description of impact
0	0	None	No part of the development work or activity associated with it is discernible
0.1-0.2	1	Negligible	Only a very small part of the proposal is discernible and/or they are at such a distance that they are scarcely appreciated. Consequently they have very little effect on the scene.
0.2-0.4	2	Slight	The proposals constitute only a minor component of the wider view, which might be missed by the casual observer or receptor. Awareness of the proposals would not have a marked effect on the overall quality of the scene.
0.4-0.6	3	Moderate	The proposals may form a visible and recognizable new element within the overall scene and maybe readily noticed by the observer or receptor.
0.6-0.8	4	Substantial	The proposals form a significant and immediately apparent part of the scene that effects and changes its overall character.
0.8-1	5	Severe	The proposals become the dominant features of the scene to which other elements become subordinate and they significantly affect and change its character.

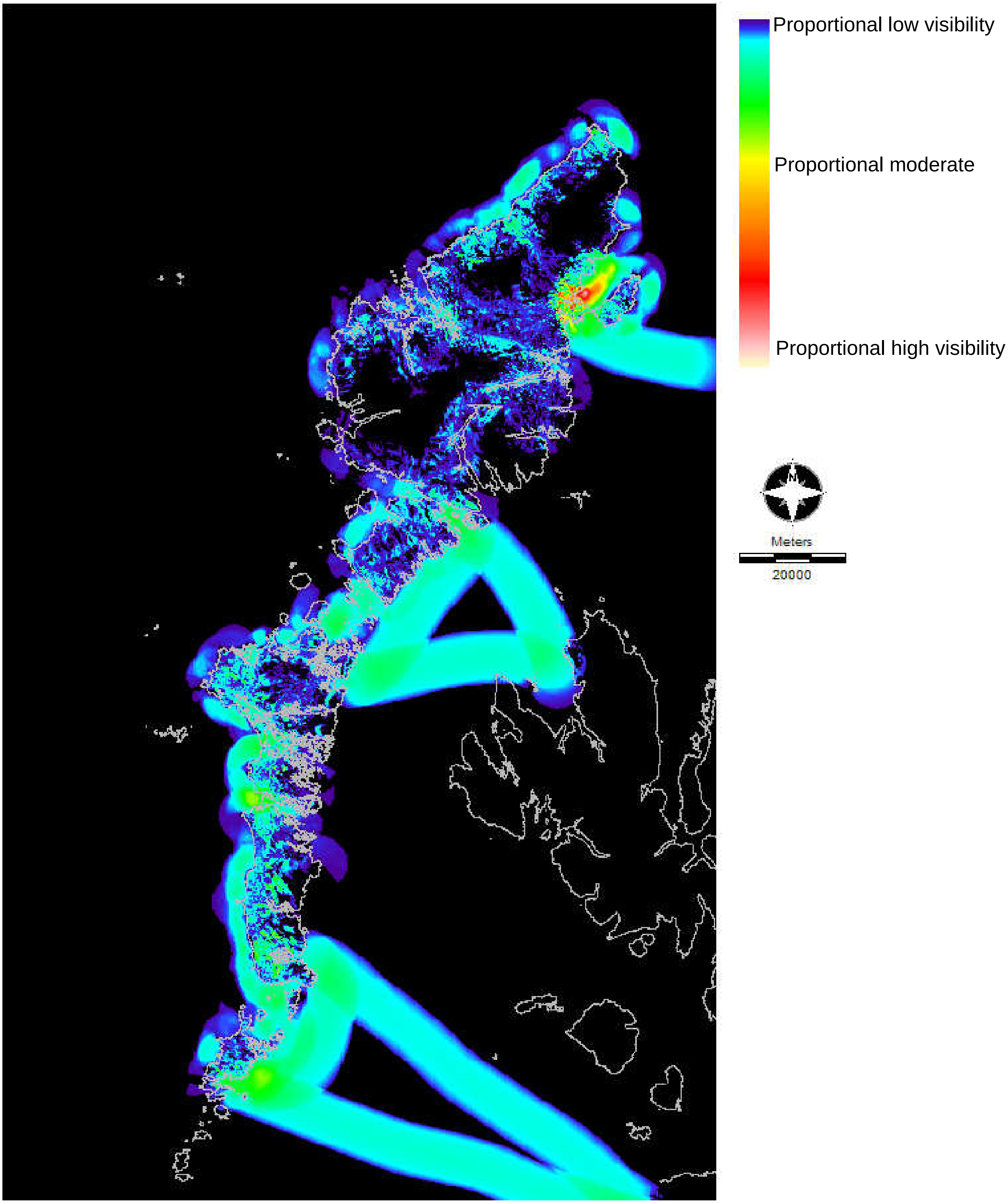

Fig. 6.5 Proportional viewshed analysis for the Western Isles, Scotland, using a 5km visual envelope.

6.3.3 Landscape Sensitivity Sub-model

Landscape sensitivity is developed from landscape character assessment (LCA) which is designed to find solutions that allow essential development to take place while at the same time helping to maintain the diverse character and valued qualities of the countryside (Swanwick, 2006). Landscape assessments are often treated as subsidiary elements on the grounds of lacking substantial evidence or due to their inherent subjectivity (Edwald, 2001), Aquaculture intrinsically has a strong relationship with its environment and as such LCA should not be treated as a subsidiary element. LCA assessments have been defined and clarified in the UK by the Countryside Agency and SNH. On a basic level an LCA attempts to classify a landscape into distinct character areas, which share common features and characteristics. It reflects particular combinations of geology, landform, soils, vegetation, land use and human settlement. It creates the particular sense of place of different areas of landscape (Benson *et al*, 2004).

Landscape character models for the Western Isles were based on information from two significant studies. Scottish National Heritage has completed a national programme of LCA for the whole of Scotland, during which an LCA was specifically produced for the Western Isles (Richards, 1998). Benson *et al* (2004) further refined the original assessments which guided the application of Landscape capacity assessments with respect to wind farm development and set out appropriate methods of landscape assessment for the Western Isles, which proposed specific landscape character type (See Appendix A2 for full details of characterization). A landscape character shapefile was downloaded from SNH while more recent data from Benson *et al* (2004) were digitized onscreen and used to update the original SNH shapefile. The resulting landscape character image is shown in Fig. 6.6. Landscape evaluation moves from characterisation, to assessing sensitivities which are based on judgments about the behaviour of a character that is subject to pressures from developments. Landscape sensitivity evaluation used here considers aquaculture developments and how they are related to landscape character. The more vulnerable a landscape is to a pressure where their key characteristics could be fundamentally altered by development then the higher is the sensitivity. Sensitivity is assessed by considering the physical characteristics and the perceptual characteristics of landscape or seascape based on the parameters shown in Table 6.2. The landscape character types were assessed on these criteria and subsequently a sensitivity rating was reached through qualitative judgment, which was adapted from that of Tyldesley *et al* (2001) as detailed in Table 6.3. Final rankings/scores defined are 1 = Least Sensitive and 5 = Most Sensitive.

Table 6.2 Landscape/seascape Sensitivity Assessment Criteria. (Adapted from Benson *et al*, 2004)

Physical	**Perceptual Criteria**
• Scale and openness	• Landscape Experienced
• Landform and shape	• Context
• Settlement	• Sense of remoteness
• Landscape pattern and foci	• Naturalness

Table 6.3 Landscape/seascape Sensitivity ratings. (adapted from Tyldesley *et al*, 2001)

Value	Sensitivity	Description of Sensitivity
1	Low	Subject to good practice and compliance aquaculture developments would normally be appropriate in these areas. No need for mitigation.
2	Low-medium	Subject to good practice and compliance with additional mitigation measures. Aquaculture developments would normally be appropriate in these areas.
3	Medium	Aquaculture development would normally be appropriate in these areas but any permission must be conditional on a mitigation package being implemented.
4	High	Aquaculture development would not normally be appropriate, in these areas. They would have significant adverse effects on the seascape. If a proposal is granted it should be conditional upon a comprehensive mitigation package being implemented.
5	Significant	Aquaculture development would not be appropriate in these areas. They would have severe effects on the seascape and effects could not be reduced by mitigation.

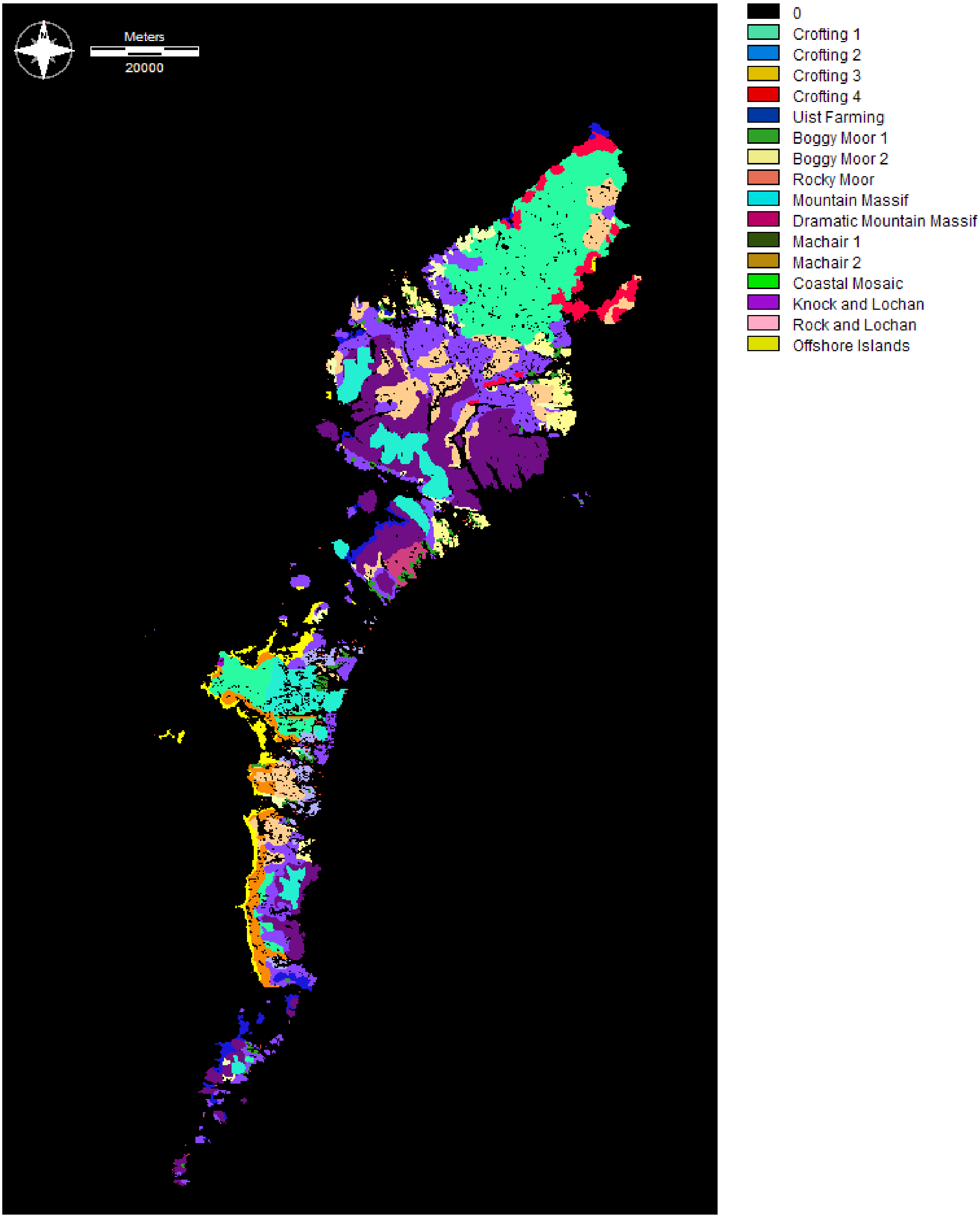

Figure 6.6 Landscape Character Types digitized and adapted from data by Benson *et al* (2004). Further information on the character types is given in A2.

6.3.4 Seascape Sensitivity Sub-model

Few studies have been undertaken in the area of seascape character assessments (SCA) in relation to aquaculture (Tyldesley *et al*, 2001; Swanwick, 2006), although some work in relation to seascapes has been carried out for offshore windfarm development (Benson *et al* 2004; Scott *et al* 2005). The SNH working definition of a seascape is *"An area of any extent which includes the sea as a key feature. Seascape has physical and experiential attributes and encompasses, the interrelationship between the sea and the sky, and may include land".* Scott et al, (2005) classified seascape units on the strategic scale of National Units as identified by Hill *et al*, (2001) whilst also including some aspects of regional seascape assessment. Hill *et al* (2001) define seascape characterization as a step to present a value free description of all key elements in seascape, where the characterization should illustrate, categorize and map seascape characters to demonstrate how one area is distinctive from another. For the whole of Scotland Scott *et al* 2005 identified thirty three units and thirteen types of character defined from which seascapes relevant to the Western Isles were extracted for this study.

Seascape evaluation moves from characterization to assessing sensitivities which are based on the schemes outlined in Table 6.2 and Table 6.3.

6.4 Overall model development

In order to describe the impact of aquaculture development on the Western Isles the three areas of landscapes, seascapes and visual impact were incorporated in an analytical manner by developing the relationships from the identification of landscape and seascape characters or proportional viewsheds into sensitivity scores. The visual and landscape sensitivity sub-models of were then combined with the landscape value sub-model by overlay to create the landscape capacity sub-model (Fig.6.7). As aquaculture is related to both onshore and offshore activities the landscape capacity model was further refined by combination with the seascape sensitivity sub-model using multi criteria evaluation where the Landscape Capacity is weighted 0.6370 which is 1/3 more important than the Seascape sensitivity which has a weighting of 0.3630 and has a consistency ratio of 0.03 which is acceptable. Lastly the overall model was reclassified to represent capacities of the whole study area in terms of aquaculture. This creates the overall Visual Capacity Model, representing the ability of scenery to accommodate different amounts of change or development of a specific type. All weights are derived from current policy guidelines (Grant, 2006).

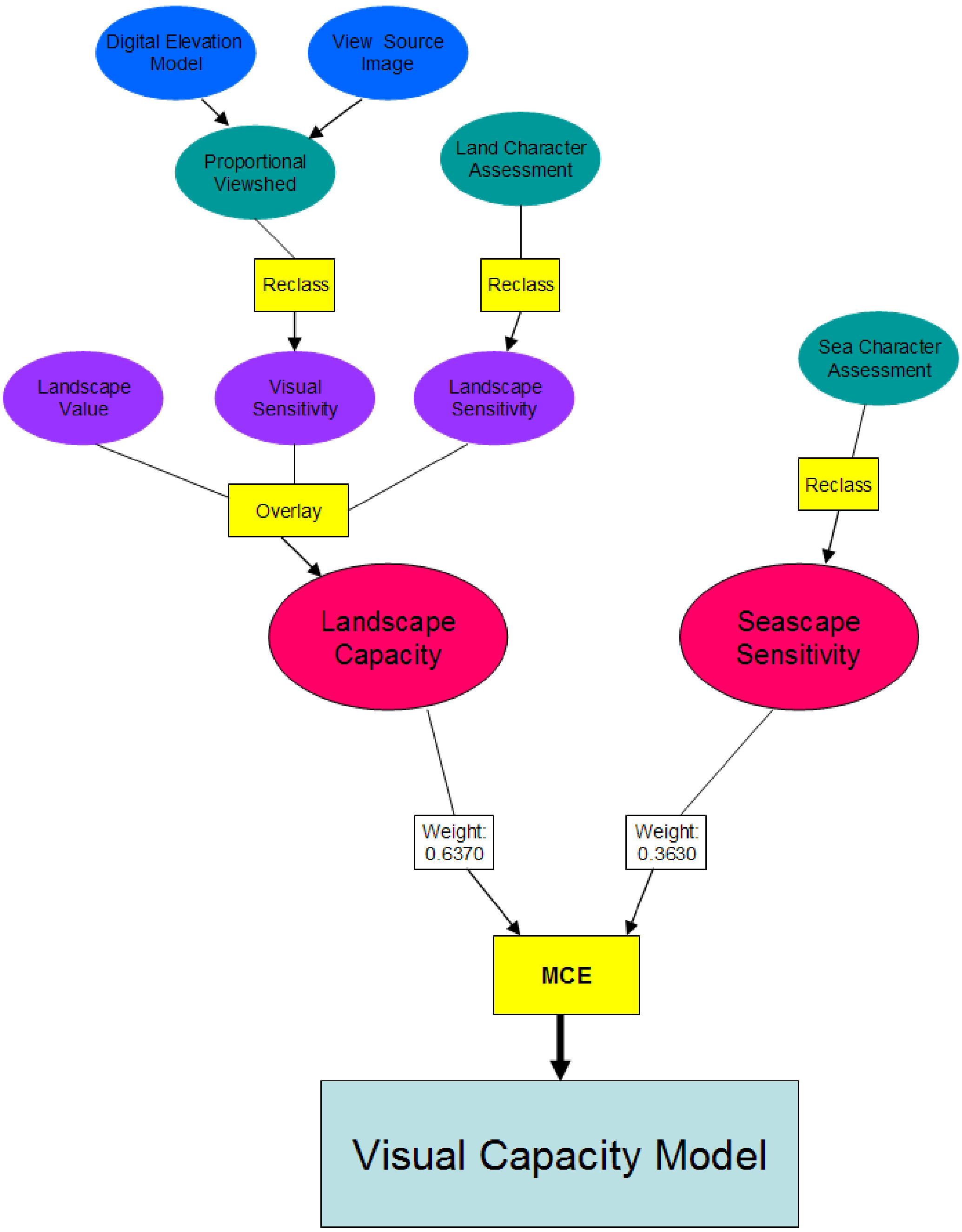

Fig. 6.7 Diagrammatic representation of the combination of sensitivity sub-models to create the overall Visual Capacity Model for coastal aquaculture in the Western Isles, Scotland.

6.5 Results

6.5.1 Landscape Sensitivity

The final landscape sensitivity outcomes indicate that most of the islands are highly sensitive in terms of landscape to aquaculture development (Fig. 6.8) and that only the Northern coast of Lewis indicates medium landscape sensitivity for aquaculture development.

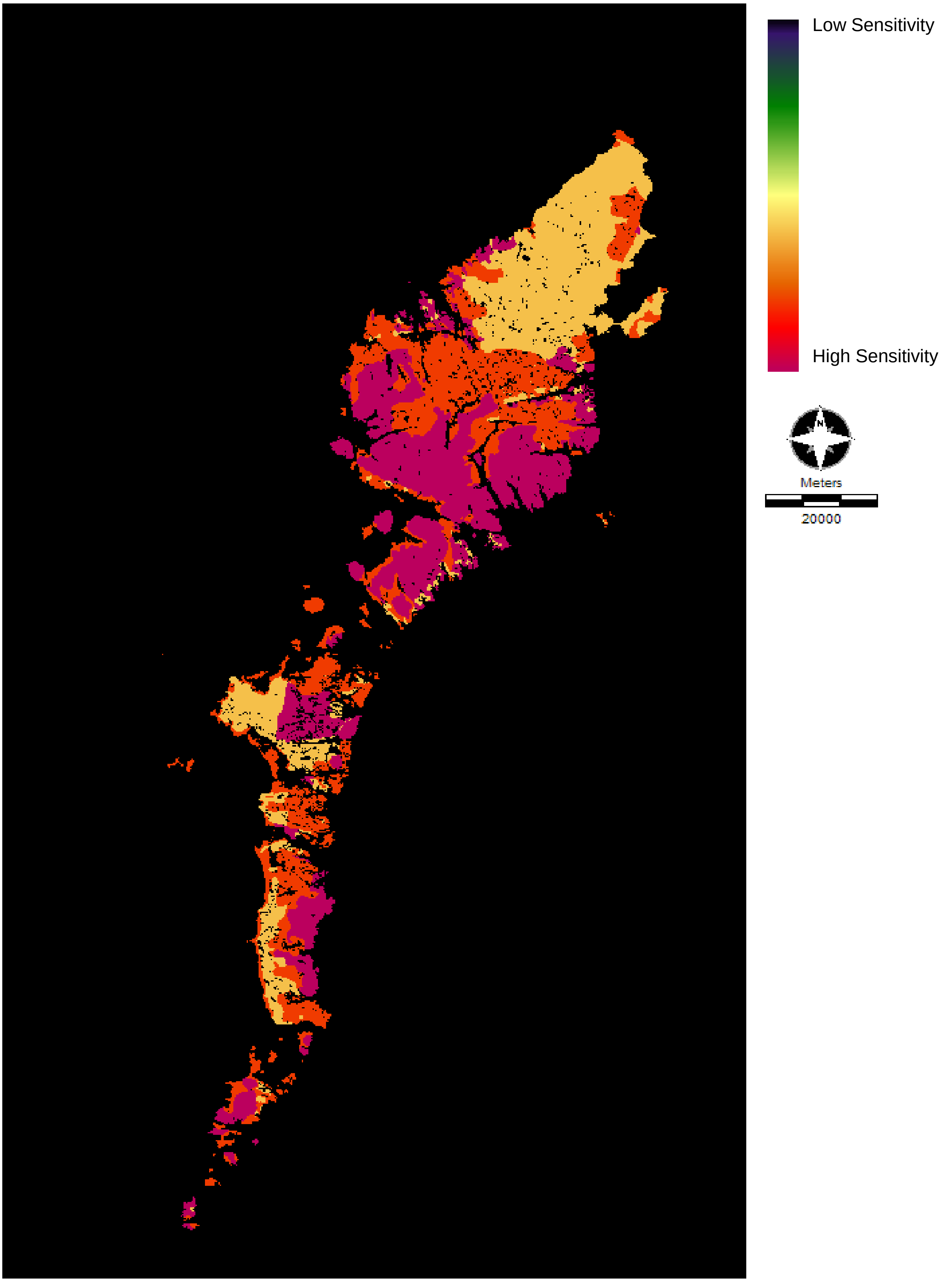

Fig.6.8 Landscape Character Sensitivity of the Western Isles, Scotland, in terms of Aquaculture Development

The legend represents the predicted land character sensitivity in relation to aquaculture and associated sensitivity rankings on a continuous scale from low to high.

6.5.2 Visual Sensitivity

The final visual sensitivity model is given in Fig.6.9. It is evident that for development of aquaculture in the majority of the isles there is negligible impact on visual sensitivity. The areas of greatest visual impact were noted around Stornoway, This is not surprising as it is the most populated area of the isles with all main routes around this area and with numerous ferry routes docking at Stornoway Harbour.

6.5.3 Landscape Capacity Model

As shown in Fig 6.6, the NSA sub-model (Fig.6.3), landscape sensitivity (Fig. 6.8) and visual sensitivity (Fig. 6.9) were combined through overlay addition to create a landscape capacity Sub-model (Fig 6.10). This solely considers aquaculture development from a land based stance. The overall premise of creating a landscape capacity sub-model which combines the sensitivities of the important areas of landscape and landscape values with visibility is to determine whether within these areas a change would be acceptable. The Landscape Capacity model results indicate that most of North Harris, South Harris, North Uist and South Uist has a low capacity in terms of aquaculture development (Fig. 6.10). While the Isle of Lewis and Barra are indicated as having a medium to high capacity for aquaculture development.

6.5.4 Seascape Sensitivity

The seascape sensitivity results indicate that most of the coastline is highly sensitive in terms of aquaculture development (Fig. 6.11). Only the seascape of the north east coast of Lewis has a low to medium sensitivity for aquaculture development.

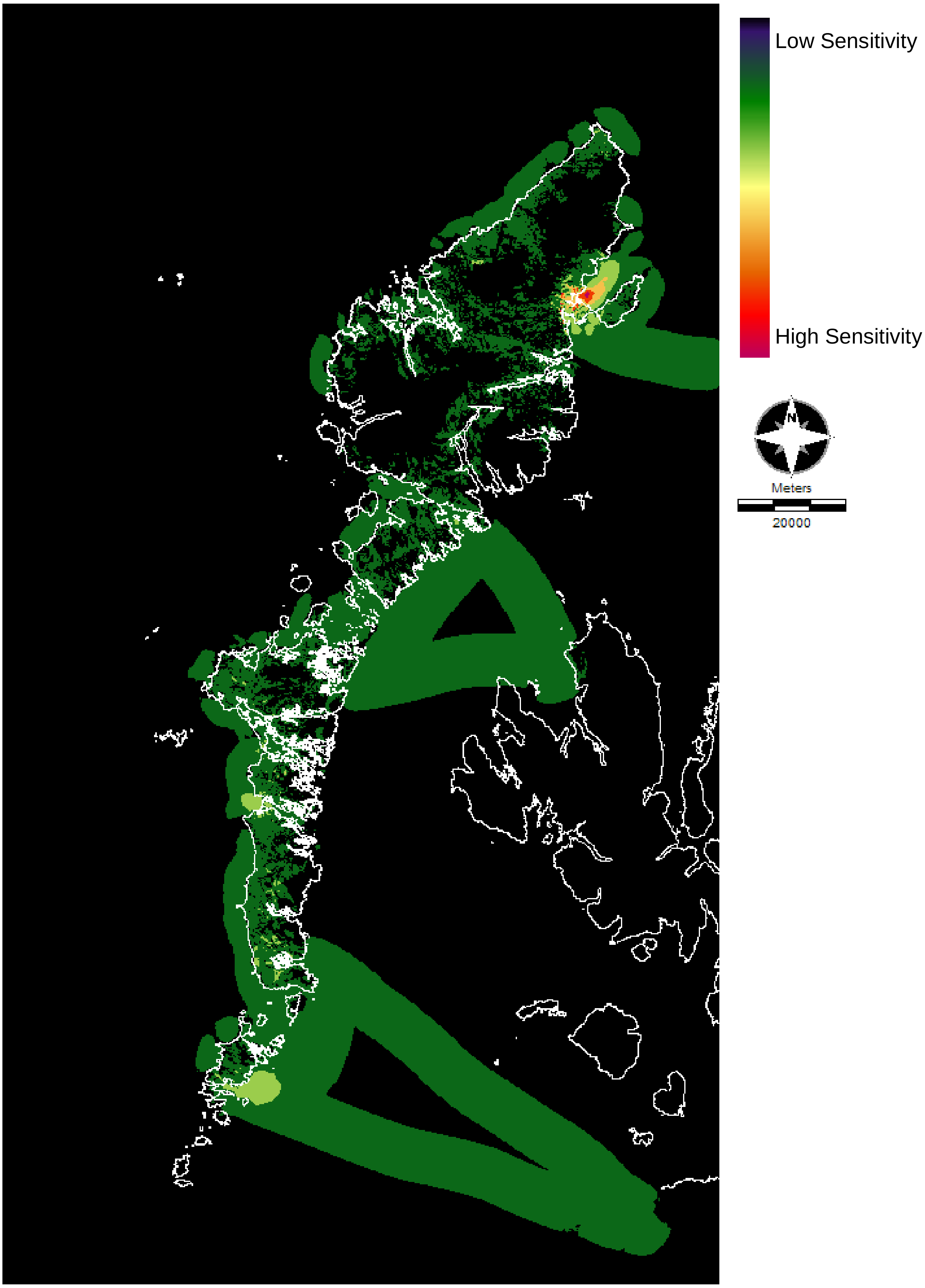

Fig. 6.9 Visual Sensitivity for marine cage aquaculture developments within a 5km buffer zone around the Western isles, Scotland.

The legend represents the predicted visual sensitivity in relation to aquaculture and associated sensitivity rankings on a continuous scale from low to high.

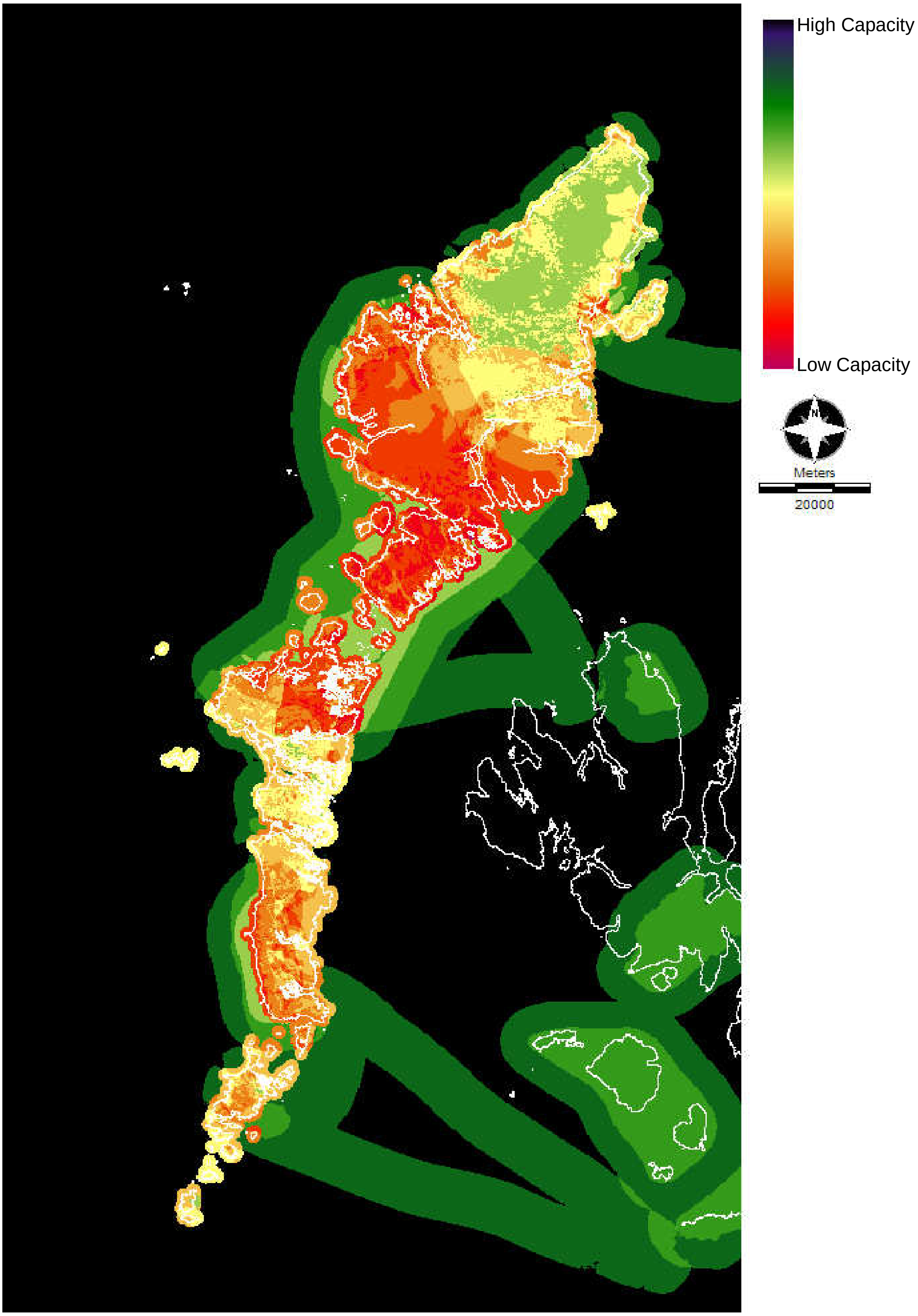

Fig. 6.10 Landscape Capacity for the Western Isles, Scotland.

The legend represents the predicted capacities for an area to incorporate new structures and the associated capacity rankings on a continuous scale from high (extremely vulnerable) to low (least vulnerable).

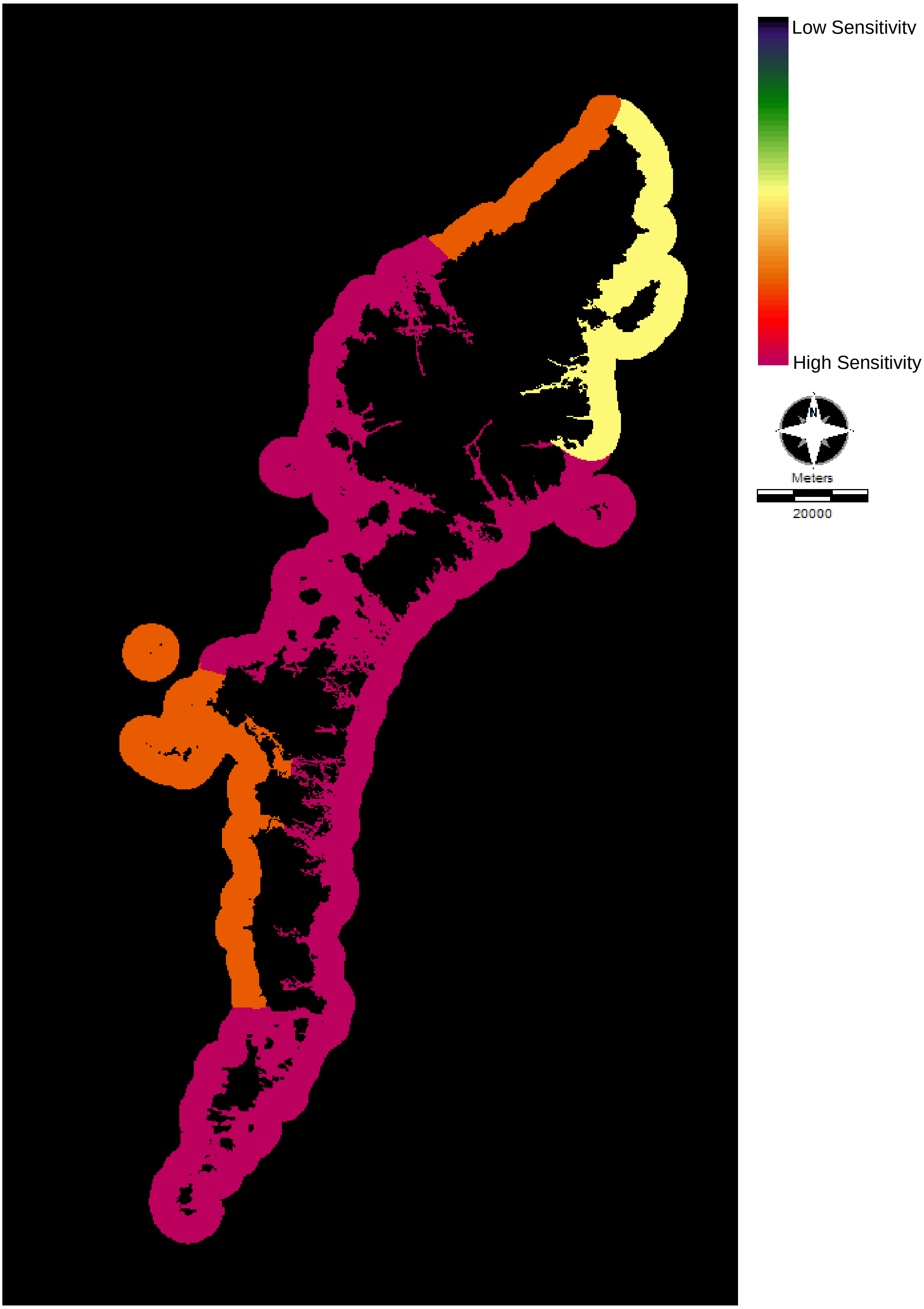

Fig.6.11 Seascape Sensitivity of the Western Isles, Scotland, in terms of Aquaculture development.

The legend represents the predicted sea character sensitivity in relation to aquaculture and associated sensitivity rankings on a continuous scale from low to high.

6.5.5 Final Visual Capacity Model

The overall visual capacity model for aquaculture development in the Western Isles (Fig. 6.12) combines the landscape capacity sub-model with seascape sensitivity through multi criteria evaluation, where seascape sensitivity is weighted with a 1/3 higher importance. The outcomes were reclassified on a scale of 1 to 10 to allow ease of interpretation of results and comparison with other studies. Relative areas of the different classifications for visual capacity are given in Table 3.

Table 6.4 Areas assigned to different visual capacities for the Western Isles, Scotland.

Category	Relative Capacity	Available Area (km^2)
1	Background	19711
2	High	3529
3		2191
4		1358
5		1030
6		678
7		1779
8		560
9		572
10	Low	192

Overall, the Visual Capacity Model indicates that the middle regions in the archipelago (Southern Lewis - including Loch Roag, Harris, Northern North, Uist and South Uist) are highly susceptible to visual impact from aquaculture development, while areas with lower susceptibility can be seen in Northern Lewis and Southern South Uist. The overlay of current fish farm production sites onto the final Visual Capacity Model shows that a high proportion of farms are currently located in high sensitivity areas while low susceptibility areas of Northern Lewis and South Uist currently have very little aquaculture activity. The Western Isles has 1324km^2 (4% of the whole study area) where there is low capacity for new aquaculture development structures. Any development, even with mitigation measures, would have a detrimental impact on its surroundings and the visual receptors who interact in these areas. About 3300km^2 (10% of the whole study area) has a moderate capacity to incorporate new aquaculture structures although any structures placed within these areas would require mitigation measures to be put in place. Lastly 6448 km^2 (20% of the whole study area) is categorized as having a high capacity to incorporate new aquaculture developments and placement within these categories areas could occur with minimal mitigation.

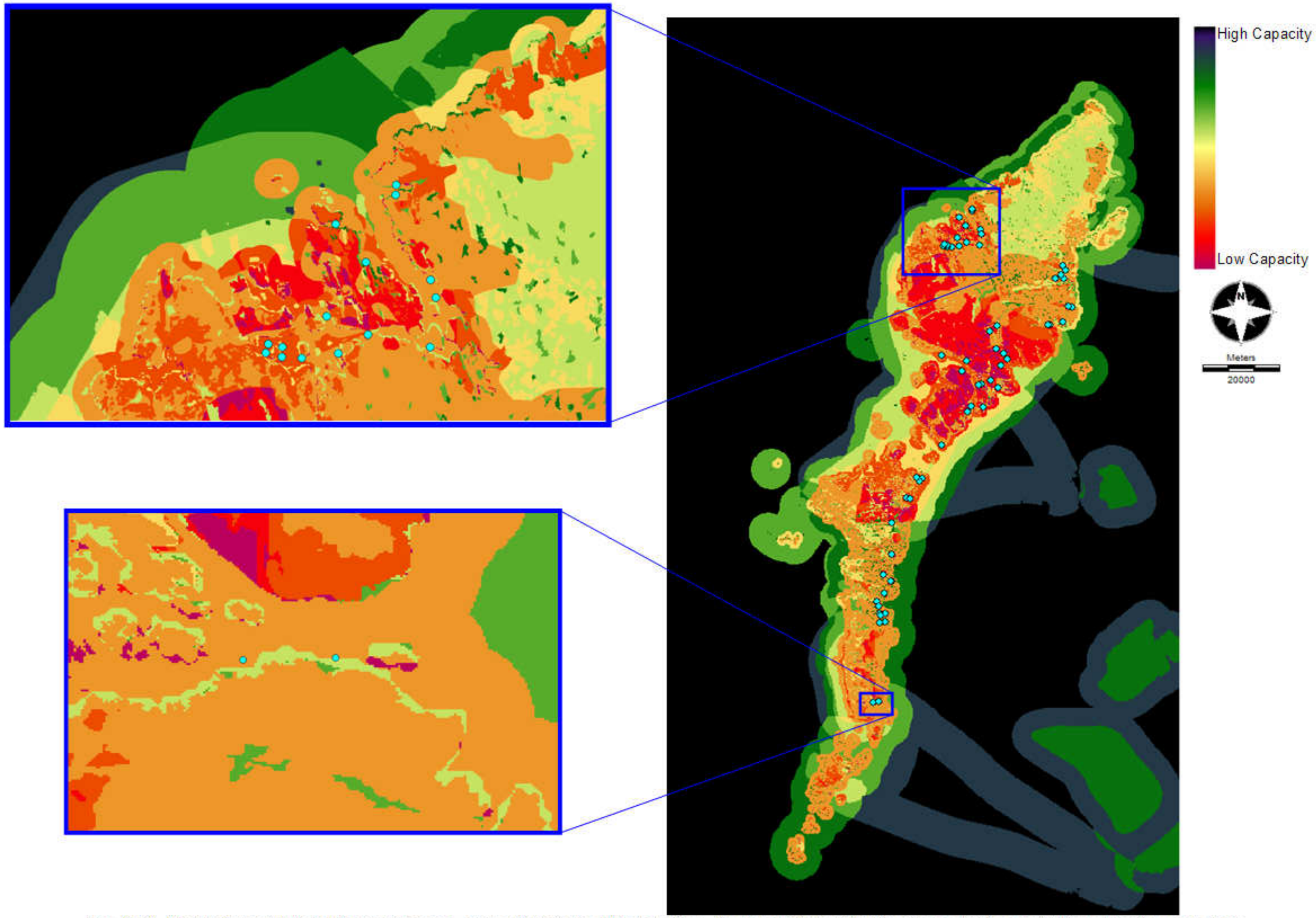

Fig. 6.12. Visual Capacity Model for marine cage aquaculture in the Western Isles, Scotland. Current fish farming activities are indicated by the cyan dots

The legend represents the predicted capacities and associated capacity rankings on a continuous scale from high capacity (least vulnerable) to low capacity (extremely vulnerable).

6.6 Discussion

Landscapes and seascapes and the overall visual capacity of different areas can be adversely affected by human activities. Most recently there have been major concerns raised in the UK in relation to the visual impacts of wind turbine and aquaculture developments (BBC, 2003; The Buteman, 2009, respectively), where considerable potential for public objection is present due to the subjective nature of existing methods of visual impact assessment This study has identified an objective, GIS-based method to assess the visual impacts of coastal and land-based aquaculture development, which accurately predicts the impact of new structures while simultaneously helping to maintain or minimize reductions in view quality, as suggested by Sander and Manson (2007). This is especially important in the Western Isles of Scotland where landscapes and seascapes and their views are a resource highly valued by local people and for the tourism industry.

Currently, landscape and visual assessments are not easily understood and may be poorly visualized. Grant (2006) reported on landscape and seascape carrying capacity for aquaculture, based on a transparent and clear methodology to determine capacity assessments for aquaculture. The proposed approach has six broad steps; a desk study to identify the attributes of aquaculture development, identify coastal character areas, carry out survey and analysis of the coastal characters, identify opportunities and constraints in relation to aquaculture in the study area, assess the sensitivities of the coastal characters to potential aquaculture development, finally produce conclusions on capacity which are accompanied by any guidance which would help to accommodate aquaculture development within the seascape area. But despite using sound methodology the fundamental application of this method to the seascapes and visual techniques for aquaculture development is clearly weak as the outcomes are hard to interpret, extremely restrictive in its application and poorly visualized. The study presented here has shown that even with the underlying complexity of landscapes and seascapes, visual aspects and landscape values can be combined and visualized, both qualitatively and quantitatively, in a coherent, flexible and reproducible manner. It can also incorporate policy and management decisions when considering locations proposed for aquaculture developments.

The Landscape assessment presented here is tailored in its approach and aimed at protecting, managing and planning for aquaculture development. The Landscape character assessment is the baseline tool for understanding the landscape and is the most appropriate starting point which is endorsed by the regulatory bodies (CA, SNH, 2002). The characters currently defined by SNH were found to be concise and an effective baseline of information to determine sensitivity rankings for aquaculture. This study showed that the sensitivity of Western Isles landscapes to incorporate any development is quite limited as most areas are deemed to be of medium to high sensitivity. This sub-model is directly related to the onshore development of facilities for aquaculture and as such if guidance was to be given there should be greater use of existing buildings etc that are already in place in the environment. As far as is practically feasible any new buildings should be kept to a minimum and if new builds were to be used they should implement high levels of mitigation measures.

As with the landscape character assessment,   the Seascape character assessment sub-model aimed to provide a robust methodology for data collection and analysis on seascapes for protecting, managing and planning of aquaculture development. The characteristics defined by Scott *et al* (2005) were found to be concise and an effective baseline of information to determine sensitivity rankings for aquaculture. The sub-model showed that the sensitivity of the coastline was predominantly medium to high while Lewis had a low sensitivity ranking on its north east coastline suggesting that there is some scope for uncontentious development in this area. Any application for development would, however, require that mitigation measures should be employed to reduce the potential negative impact.

Visual analysis using Viewshed approaches within GIS has been shown to be a powerful tool for visual assessment through successful implementation (Orland, 1994; Perez *et al*, 2003; Kuenemerle *et al*, 2009). The greatest strength of implementing GIS-based visualization is that it extends beyond the simple visibility analyses that are currently employed (Swanwick, 2006).The visualization techniques employed in this study incorporate complex issues and makes them available to stakeholders in a more easily understandable form. The proportional visibility of locations and the effects on visual receptors can be easily explored from different perspectives.

Visibility analyses have become a more accessible modeling tool in the recent years due to advances in computing power and software packages (Rana, 2003). Viewshed analysis has been successfully applied in valuing open spaces (Sander and Polasky, 2008) to spatially estimate direct use value of ecosystem services (Chen *et al*, In press) and in other areas (Geneletti, 2008). The definition of a visual effect relates to the composition of the available views. This composition can be altered by any proposed aquaculture developments. It is those changes in compositional view that society will respond to and this is the impact that needs to be assessed in terms of visual impact. The approach presented here applies a visual analysis tool that is practical in its approach and can be driven by specific policies and frameworks.

The sensitivity of the Western Isles coastline in terms of visual impact is predominantly low in most locations and so, if carried out carefully, there is probably good scope for further development when considering this parameter alone. By contrast, there are areas with a higher visual sensitivity, for example near Stornoway, South Uist and Barra. Clearly any development in these locations could only be supported if mitigation methods were employed.

All these component sub-models have intrinsic value and could be employed as stand-alone tools. However the use of a GIS framework confers the ability to combine these outcomes into a structured visual capacity model for the whole of the Western Isles. Development of visual capacity values depends not only upon objective components of the model, but also on more subjective societal matters and so the process can be a contentious issue which is both problematic to achieve and diverse in it's possible outcomes. The final model presented in this study combined for the first time the four major areas of landscape values, landscape sensitivities, seascape sensitivities, and visual sensitivities in a structured spatial model which is relatively easy to modify or update. Overall, this showed that those islands in the middle of the archipelago (Harris, etc) are unlikely to be able to absorb any further marine aquaculture development without mitigation measures. By contrast, aquaculture could develop in Northern Lewis and in South Uist with much less of a requirement for mitigation measures. Overlaying the currently active fish farms onto the overall visual capacity model outcome shows that a high proportion of farms are currently located in high sensitivity areas, while low susceptibility areas of Northern Lewis and South Uist currently have very little aquaculture activity. On one hand, it is interesting to speculate whether all existing sites would be granted licenses under the developing regulatory regime which requires more thorough visual impact assessment. On the other hand, the pre-existence of farms in these locations now sets a precedent and resolution of the legal issues, alongside the requirements for economic development of communities such as those in the Western Isles and food security issues at a wider level, may require considerable time and effort. Clearly, if properly used and fully exploited, objective GIS modelling has a significant part to play in resolving these matters.

This study has highlighted the advantages and strengths of approaching landscape and seascape capacities by combining visual assessments and landscape values in a quantitative methodology that is suitable for supporting aquaculture development. The assessments of sensitivity or capacity rely on objective visual assessments incorporated with more subjective societal judgments and where possible these judgments need to be driven by stakeholders and coherently expressed (Scott and Benson 2002). Environmental surroundings contribute on many levels to our daily lives and ensuring that negative impacts are kept to a minimum should be of prime importance. There can be no doubt this is a highly complex issue to address and the identification of future landscape change serves to highlight consequences of underlying, social constructions of landscape stewardship (Simpson *et al* 1997). GIS modeling is capable of managing this range of qualitative and quantitative parameters.

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6.9 Appendix: Supplementary Tables.

A1. Landscape Characters relevant to the Western Isles.

Landscape Character Types	Total Area Ha	Description
Crofting 1	10397	Settlements predominantly Northern Lewis where crofts sit on open, exposed moorland edges and sweep down to the sea and the strips are very linear and uniform.
Crofting 2	7252	Crofting landscapes which have a linear field pattern imposed on a more complex landform of rocky or boggy moorland.
Crofting 3	4766	Irregular field pattern on complex landform adjacent to Knock and Lochan, rocky moor and mountain massif
Crofting 4	9509	Crofting occurs only in Uists characterized by large rectangular field patterns on a very flat landform studded with lochs
Uist Farming	170	Small area made distinct by stone field boundaries and large farmhouses suggesting agricultural rather than crofting relationship with the land.
Boggy Moor 1	76665	Large-scale undulating peat moorlands lochans are occasional rather than a main feature
Boggy Moor 2	32188	Large-scale undulating peat moorlands where lochans are numerous creating a strong patterning and interplay of land and water with reflective effects
Rocky Moor	51995	Irregular topography of rocky knolls interlocked with peaty moorland vegetation and occasional small lochans.
Mountain Massif	69881	Lower, rounded, shouldered peaks or ranges which gradually from the surrounding landscapes
Dramatic Mountain Massif	18815	Mountains are more ‘dramatic’ because they rise suddenly from the landform or the sea, have an impressive scale or ‘apparent scale’ in relation to their surroundings or have distinctive and complex landforms.
Machair 1	8150	Simple landscape found in the Uists, of fairly flat, extensive grassland with settlement kept to the landward fringes, protected by linear dune systems and very long, sweeping sandy beaches.
Machair 2	3945	Dune systems and beaches which are more complex and of a more intimate scale surrounded by rocky headlands. Settlement is often dispersed throughout the machair grassland which is less extensive and more influenced by rocky landform.
Coastal Mosaic	4876	Intricate arrangement of sea lochs and fragmented land patterns gradually breaking up into small islands and skerries. Inland the influence of the sea is very evident in the colours of the marine flora which skirt the base of all the rocky shores around the lochs, tidal markings also very apparent. Key feature is the interplay of land and sea.
Knock and Lochan	8896	Complex landscape of irregular knocks (massed boulders on bedrock outcrops) interspersed with small lochans. It is sparsely vegetated and predominantly unihabited. Where it meets the sea there is a coastline of rocky promontaries, small bays and offshore skerries.
Rock and Lochan	2775	Small sub area of Knock and lochan in south east Harris, it is distinct from knock and lochan mainly in the amount of bare rock visible and the north west/south east orientation of the patterning of rock formations and therefore the lochans. The landform elements are smaller scale and flatter, being comprised mainly of low ridges.
Offshore Islands	1090	Number of predominantly uninhabited offshore islands, primarily rocky moor with rugged coastlines

A2 Seascape Characters relevant to Western Isles

Seascape Unit	**Seascape Character Type Present in Unit**	**Key Characteristics**
12	Type 13: Low Rocky Island Coast	-low rocky coastline, cliffs and fragmented coastline in places backed by moorland -sparsely settled. Small crofting settlements along coastline. Large settlement at Stornoway with some industrial development, airport and busy port. -parts of this landscape feel remote expect Stornoway area.
13	Type 13: Low Rocky Island Coast	-Low rocky coastline rising to cliffs in places -backed by moorland behind coastal fringe of crofting settlements -linear coastline with open views of atlantic occasionally limited by undulating landform -exposed
14	Type 13: Low Rocky Island Coast Type 9: Sounds, Narrows and Islands	-heavily indented and rocky fragmented coastline of eastern Harris and the Uists with distinct hinterland; contained sounds and narrows also present on this western coast. -settlement small scale with traditional crofting -large areas of remote undeveloped land.
15	Type 13: Low Rocky Island Coast Type 12: Deposition Coasts of Islands. Type 9: Sounds, Narrows and Islands.	-fragmented coastline and mountainous hinterland -high mountainous areas -many uninhabited islands
16	Type 12: Deposition Coasts of Islands.	-sparse, traditional crofting settlements -wide open views -Exposed and seascape dominated experience
17	Type 9: Sounds, Narrows and Islands. Type 12: Deposition Coasts of Islands. Type 13: Low Rocky Island Coast	-small scale machair bays nestled in low lying rocky coastlines -mountainous hinterland -small isolated crofting settlements close to the coast - series of unhabitated and fairly dramatic islands to the extreme south -scenic, isolated with qualities of exposure and remoteness

A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Chapter 7

Holistic GIS modeling tool to support marine cage aquaculture site selection.

7.1 Introduction

A recent collaborative study between some of the important governing bodies of Scotland's aquatic resources, Fisheries Research Services (FRS), Scottish National Heritage (SNH) and the Scottish Environmental Protection Agency (SEPA) has identified that Scottish seas are changing in a way that may cause a disturbance in the distribution and abundance of marine species and could lead to changes occurring in the Scottish coastlines (Baxter *et al* 2008). 2008 also saw an advancement in marine environmental policy with the introduction of the Marine Strategy Framework Directive 2008/56/EC (OJ L164, 25/06/08). The intention of the Marine Strategy Framework Directive (MSFD) is to implement, by 2020, improvements in the ecological health of our seas. For this improvement to be realized there needs to be substantial assessments of the current sea states. While in Scotland this is progressing well, there is a need to identify and resolve the complex issues encountered in the coastal zones of all EU member states. The MSFD is actively promoting the establishment a framework to protect the marine environment with the expectation that this will lead to an overall improvement in the marine environmental status.

Aquaculture in Scotland needs to consider this tendency for environmental degradation and address its coastal management plans to ensure that it minimizes its contribution to this disturbance. There is scope for improvement in management tools and for development of a better strategy that is spatial in nature, flexible, and easily updateable when new information becomes available. This approach is supported by the current initiatives of the Food and Agriculture Organization of the United Nations through promotion of the Ecosystem Approach to Aquaculture (EAA) and the Ecosystem Approach to Fisheries (EAF) (Soto *et al*, 2008). The approaches and guiding principles promoted by FAO are aimed at a holistic approach that focuses on the entire ecosystem through adaptive management. The approach explored in this study strongly supports the implementation of GIS for EAA planning, as it encourages stakeholder involvement and development of integrative policies including, ecological, economic and social realms.

There is a requirement for a structured approach to selection of sites for aquaculture development. This study aimed to further this research by developing a holistic GIS-based tool for aquaculture. Management practices that are able to guarantee the sustainable management of coastal zones are required (Turner and Bower, 1999). This type of approach needs to have the capability to manage and analyse a varied amount of data that may include features such as site selection, conservation and waste dispersion. The unfavorable impacts of aquaculture are widely documented and the current major areas of concern are of organic enrichment (Kawahara *et al*, 2009), effects on biodiversity (Beardmore *et al*, 1997), landscape, seascape and visual impacts of aquaculture development (Grant 2006) and medium to long term lack of sustainability (Naylor et al 2000).

Whitmarsh and Palmieri (2009) implemented a survey-based approach to evaluating public and stakeholder attitudes in Scotland and their survey results for the Western Isles indicated a marked preference in favour of aquaculture expansion. With this clear public and stakeholder support for aquaculture development, the Western Isles is an ideal setting in which to explore the use of GIS tools for aquaculture development. There is undoubtedly a requirement to ensure that decision support tools are capable of modelling the actual and / or future impacts of fish farms in a way that takes account of physical, ecological and infrastructural factors on environmentally sensitive parameters and areas or places of conservation interest in the coastal area of Scotland.

7.2 Geographical Information Systems (GIS)

GIS for application in the aquaculture sector has been strongly promoted over the past twenty years (e.g. Nath *et al,* 2000; also see GISAP http://www.aqua.stir.ac.uk/aqua/GISAP and FAO GISFish http://www.fao.org/fi/gishfish/). Promoting the importance of GIS for aquaculture and fisheries management and planning has been influenced by the FAO (Meaden and Kapestsky, 1991; Kapetsky and Nath 1997: Kapetsky and Chakalall 1998; Aguilar-Manjarrez and Nath 1998; Graaf *et al*, 2003; Jenness *et al*, 2007; Kapetsky and Anguilar-Manjarrez, 2007). GIS models have been previously successful in implementing aquaculture placement (Halide *et al*, 2009; Hossain *et al*, 2009 and Mahalakshmi and Ganesan 2009), modelling biodiversity (Maxwell *et al*, 2009), modelling waste dispersion (Corner *et al*, 2006; Cromley *et al*, 2009; Shih *et al* 2009) and visual assessments (Benson *et al*, 2004 and Grant, 2006). Whilst individually these studies may be based on strong models, many are single issue tools which operate at the level of single or limited sites. Consequently, there is a growing need for closer integration so as to consolidate all the available information through policies and frameworks. GIS has the ability to consolidate spatial information which can then be manipulated to address issues pertaining to multiple uses and wide areas of the coastal zone. The coastal zone is unique in its diversity of users that include residents, tourists, fish farms, fishers and ferry routes. In the United Kingdom, governance of the marine environment at national and regional level is often applied inconsistently and on occasions there can be little apparent unity between agencies and community groups concerned with management of the aquatic environment. GIS can establish a framework for all these areas and concerns, and can assist with positive development while still ensuring that the environment is not degraded despite the number and variety of multiple uses. In particular, aquaculture cannot be sustainable and driven forward in the Western Isles without close consideration of all other users as well as considerations of the coastal environment. It is essential that these issues are considered in a rational, balanced manner which can accommodate complex trade-offs among contributing factors. The marine spatial GIS framework implemented here was designed to consider issues pertaining to coastal aquaculture and provide a platform for improved information availability, better coordination of decision making across agencies, the encouragement of community involvement and creating mechanisms for pre-emptive conflict management and to create a management framework for best practice solutions based on policy frameworks.

7.3 Overall Model Framework

The conceptual framework implemented in this study was designed to identify the most appropriate areas for sustainable aquaculture development whilst still considering any possible conflicts with particular reference to conservation issues. This framework (Fig. 7.1) is capable of addressing a number of possible conflicts and identifying appropriate development areas with the flexibility of being rapidly updated as information and legislation changes.

The components of any decision support system (DSS) must be chosen for their relevance to the study area. In this study four major topics for management of aquaculture development in the Western Isles were explored: site location, particulate dispersion impacts, biodiversity sensitivity analysis and visual landscape and seascape analysis. These aspects were considered to be the most relevant for the Western Isles although there are numerous others that could have been developed such as socio economic factors (Stickney and McVey 2002). The component sub-models have the additional ability to be combined flexibly into an overall aquaculture decision support system and from this, two approaches can be taken; the combination of information and the drawing out of information.

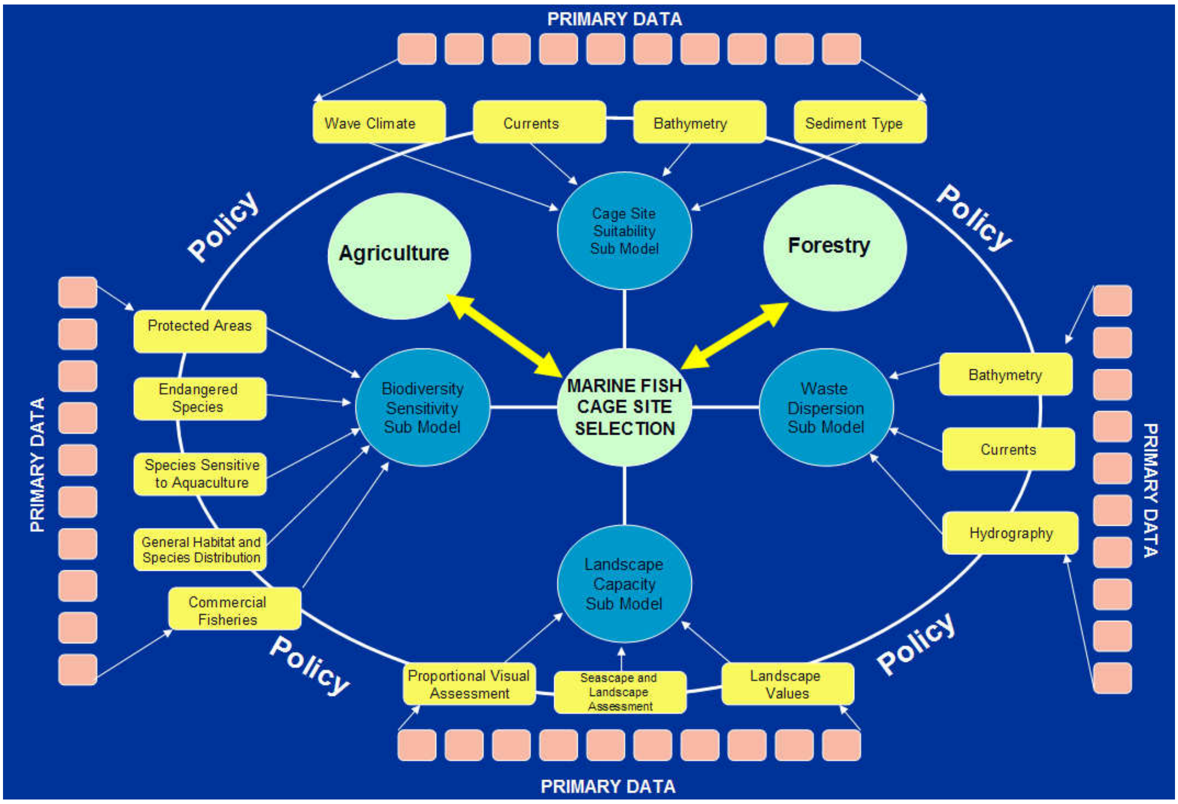

Fig. 7.1 Conceptual GIS model framework providing decision support for marine aquaculture and how it is possible to interlink other activities relevant to the study area within the GIS framework.

7.4 Marine Aquaculture Decision Support System Components

Each of the four sub-models defined in the framework required a different management approach and therefore different GIS models were implemented to deal with each problem. One over-riding strength in all the sub-models is the open management process that can be easily followed and can be driven by policies, agencies and stakeholder views.

Cage site suitability Sub-model

The first sub-model considered was site location on a regional scale, developed from selection criteria consisting of environmental variables relevant to cage design and technology. Much of this information pertaining to the siting of fish cages in the coastal zone is spatial in nature and therefore the most efficient method of manipulation and modeling this type of data is through GIS. This initial sub-model is fundamental and establishes the basis and locations for applying additional sub-models and decision support tools for multi-site aquaculture planning.

The cage suitability sub-model was developed to address the importance of siting different types of cage technologies based on their physical design capabilities. This sub-model incorporated the previously identified important criteria of currents, bathymetry and wave climate. The final output cage suitability sub-model visualized and quantified the extent of appropriate areas for allocation of aquaculture development based on the physical environment (Fig 7.2). The models for the KFF LMS sheltered inshore cages (Fig 7.2A) show that ideal locations are restricted to inshore sea lochs covering an area of approximately 91km^2 (10% of the study area). By contrast, the models for the semi exposed KFF C250 cages show that approximately 1543km^2 (37% of the study area) of coastal waters are favourable (Fig. 7.2B). Most of these areas can be found in the sea lochs as well as in some open coastal areas. The KFF C315 exposed cage type (Fig. 7.2C) has the greatest number of suitable areas of the three modelled at approximately 3103km^2 (65% of the study area). Almost all of this is located offshore as the design of the cages uses a net with a depth of between 15 and 25m restricting their ability to be placed in shallower seas.

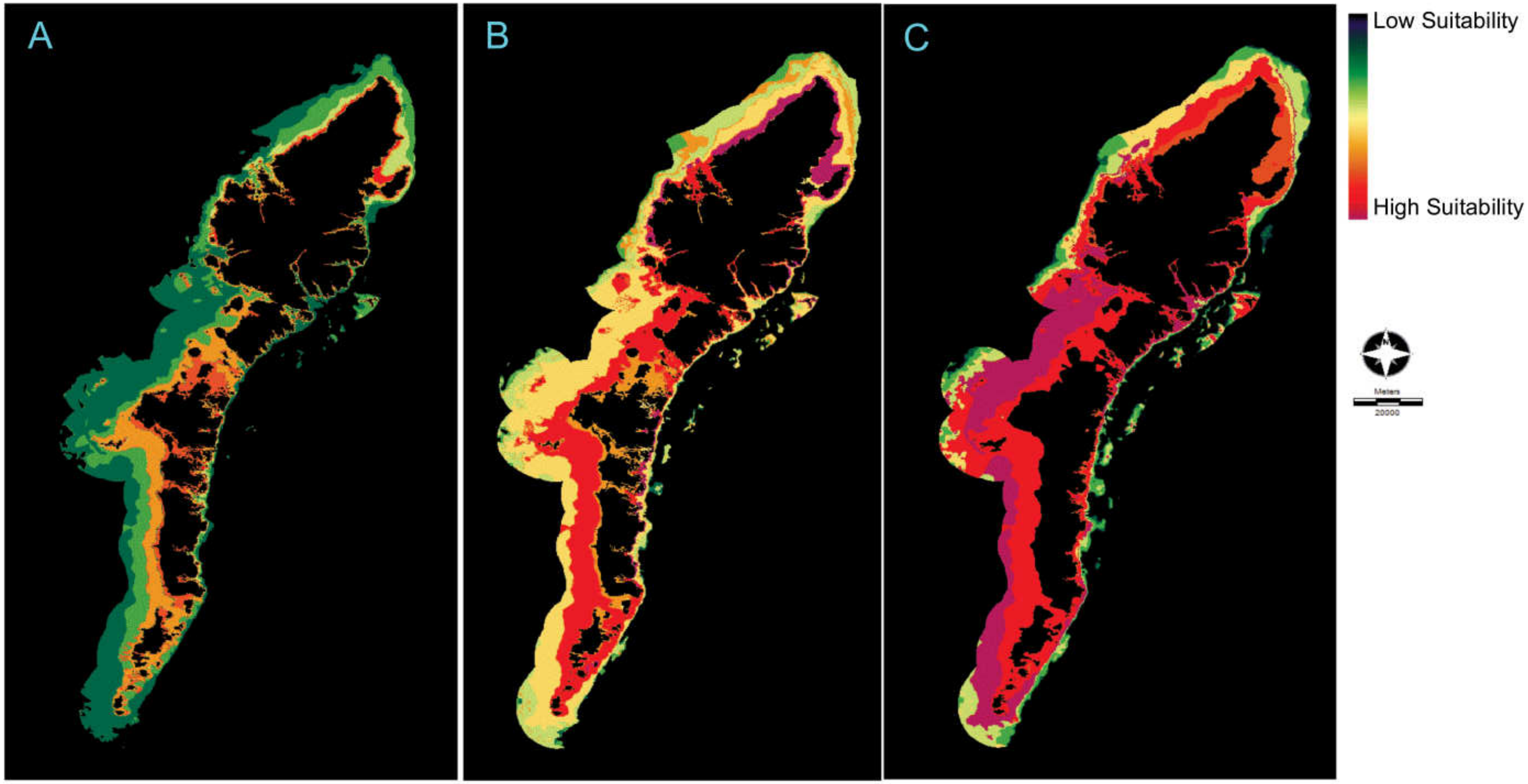

Fig. 7.2 Cage suitability sub-models for three cage designs A = LMS (for sheltered environments), B = C250 (for semi-exposed environments) and C = C315 (for exposed environments).

The legend represents the predicted suitability for an area to incorporate new structures and the associated suitability rankings on a continuous scale from low (extremely unsuitable) to High (Highly Suitable).

Biodiversity Sensitivity Indicators sub-model

As aquaculture has a close relationship with its environment any development needs to ensure that it does not come into conflict with the important ecologically sensitive marine species and habitats of the Western Isles. The second sub-model was designed to identify species distributions and further classify habitat suitability models for the species under study. This sub-model is based on the implementation of Habitat Suitability Modeling which is, in turn, based on ecological niche theory (Grinnell 1917; Hutchinson 1957), where the fundamental argument is that individual species will thrive within specific ranges of environmental conditions. Again, this is ideally suited to modelling within a GIS environment due to the spatial nature of this concept.

A Biodiversity sub-model was developed in order to identify ecologically sensitive habitats and incorporate both land and marine species of conservation concern (Fig. 7.3). The biodiversity sub model aimed to address the identification of sensitive areas not just for individual species but also to include habitat suitability. This sub model incorporated the important criteria of protected areas, endangered species, species sensitive to aquaculture, commercial fisheries and general local habitat and species distribution of importance for the Western Isles. The resulting sub model is highly versatile and flexible in identifying areas of coastal vulnerability to aquaculture development. The coastal areas for the Western Isles are among the most biologically diversified in Scotland and can be defined also as a highly productive environment for aquaculture production. There is a great need to balance both these factors. The EU Marine strategy has a defining principle of ecosystem-based marine spatial planning and aims to achieve a good status for the environment. Addressing the biodiversity of the Western isles in the manner of the model used here is in line with their guiding principles.

The final Biodiversity sensitivity model indicates that the Western Isles has 1168km^2 (4% of study area) highly sensitive biodiversity areas in relation to aquaculture (indicated by the Red and Burgundy). The final Biodiversity sensitivity model indicates that the Western Isles has 20595km^2 (65% of study area) low sensitive biodiversity areas in relation to aquaculture (indicated by dark blue). This provides clear indications of the areas which are sensitive to aquaculture development in the Western Isles where many of these same areas are also important for present and future development of aquaculture. The model confirms areas previously known to have a high overall biodiversity sensitivity, such as in Loch Roag and the north-east of North Uist, (Malthus *et al*, 2006), but also highlights other areas which were not previously considered such as the east coast of Benbecula.

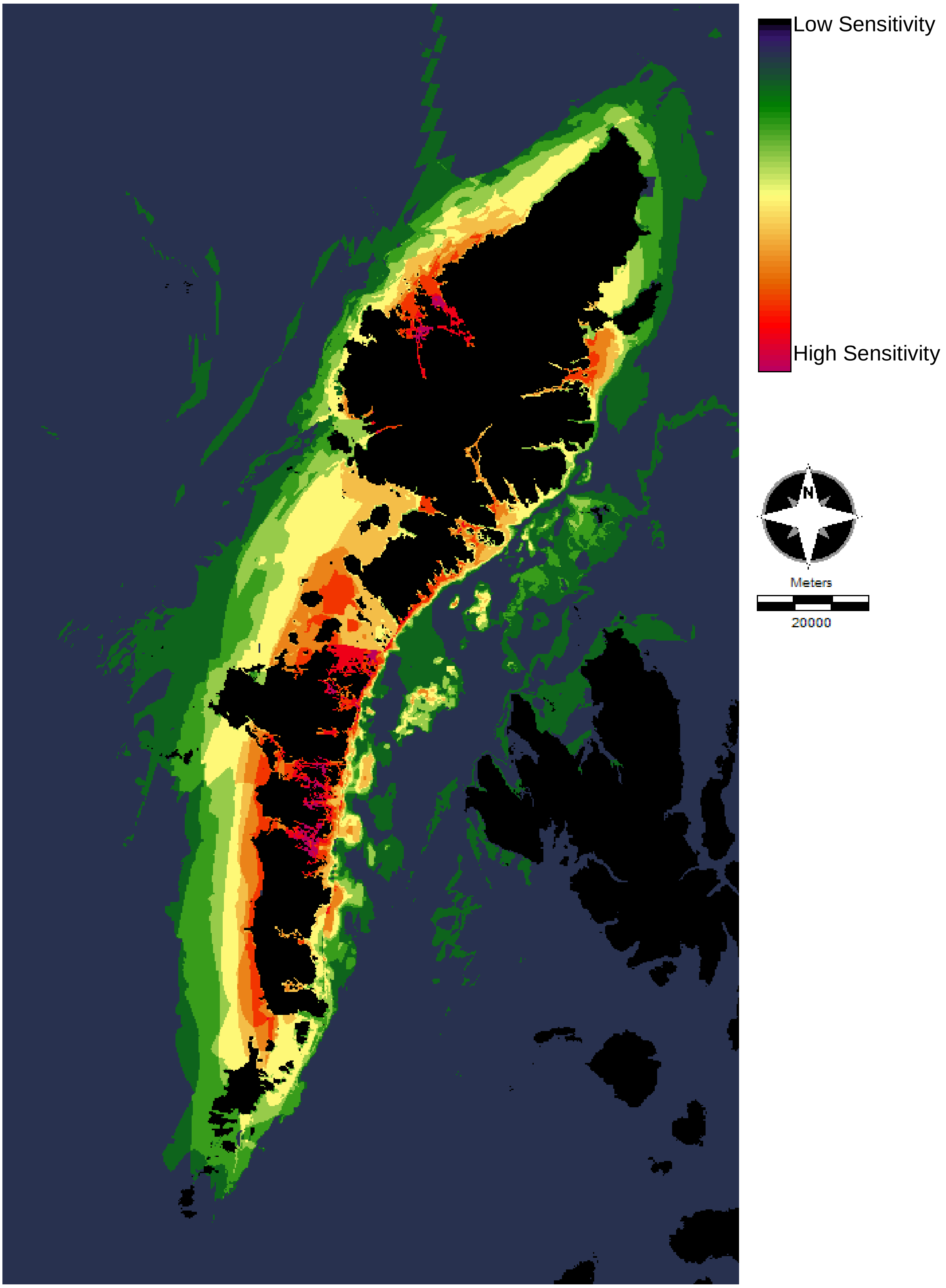

Fig. 7.3 Biodiversity Sensitivity Indicators sub-model for the Western Isles.

The legend represents the predicted species distributions and associated sensitivity rankings on a continuous scale from low to high.

Particulate Dispersion sub-model

Aquaculture activities release particulate material in to the environment in the form of uneaten feed and faecal matter and this release of particulates can negatively degrade the environment (Iwama, 1991; Naylor *et al*., 2000; Mirto *et al*., 2002; Holmer *et al*., 2003; Wilson *et al*., 2004; Cancemi *et al*., 2006). Particulate dispersion patterns are thought be mainly influenced by local current velocities, bathymetric profile, farm production values, settling velocities, cage movements and resuspension (Cromey *et al*, 2002; Doglioli *et al*, 2004; Corner *et al* 2006; Giles *et al*, 2009). The extent to which the particulate dispersion pattern has a degrading impact on the surrounding environment is generally thought to occur within a maximum radius of approx one hundred metres from the cages (Holmer, 1991 and Pearson and Black, 2000). Currently Scotland has a narrowly focused approach to particulate waste dispersion from fish cages (Telfer *et al*, 2009), and the sub-model developed in this study aimed to model dispersion patterns from fish farms on a multi site level by simple consideration of the hydrodynamic nature of the environment.

A particulate Dispersion sub-model appropriate for large-scale multi-site analysis was developed in the form of a footprint model (Fig. 7.4), wholly with the GIS. The results from this sub-model indicate that the maximum current velocity is to some extent correlated to the validated waste dispersion pattern. As such, the most practical application of multi site particulate modeling from fish farms should be to implement maximum current velocity at a one metre resolution.

Waste from aquaculture can be described as the most detrimental impact that aquaculture has on its environment. This degradation of the environment can lead to a high degree of conflict between users. Thus, the ability to implement such a model in a GIS environment is extremely relevant in the current climate of change and could bring all agencies involved in coastal management together if such a system could be universally adopted by the Scottish government.

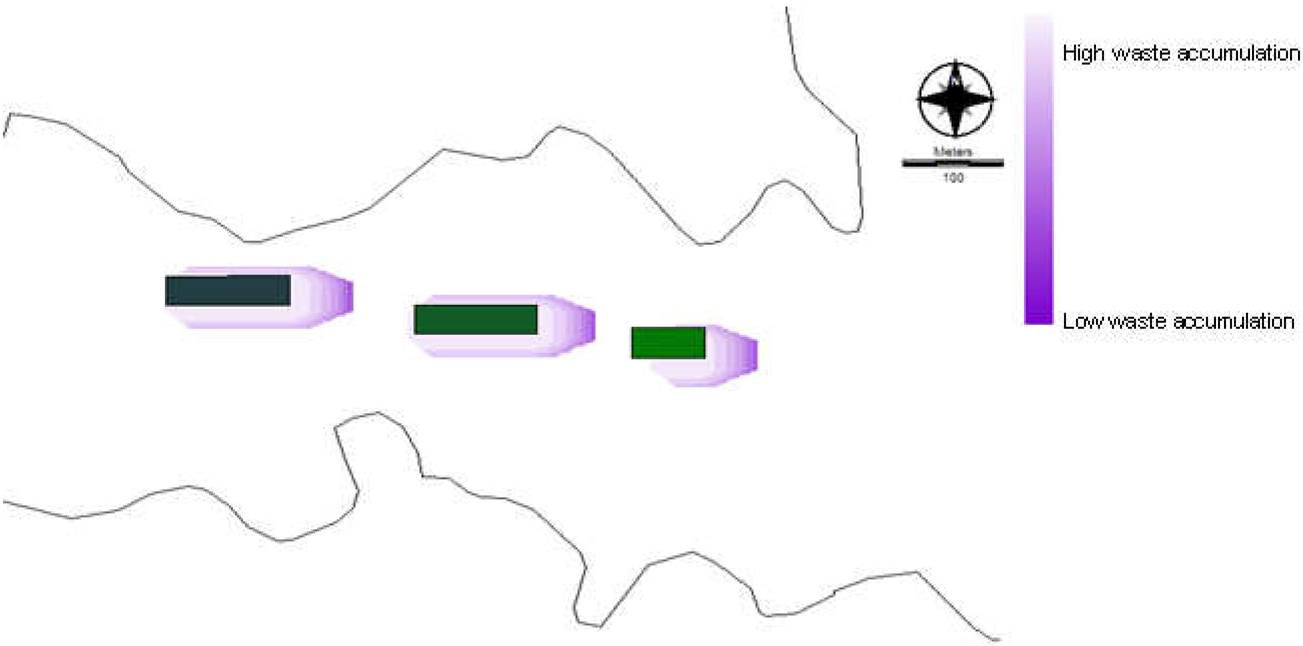

Fig. 7.4. Representative example of multisite waste GIS dispersion model showing three active fish farms and their waste footprint.

Visual Capacity sub-model

A currently emerging area of conflict for any aquaculture development is its visual impact on the environment and this has become of greatly significance in Scotland where it may potentially impact on scenic beauty (The Buteman, 2009). Challenges of this kind have been highlighted previously (Opdam *et al*, 2002: Tress *et al*, 2007: Wissen *et al*, 2008) and the fourth sub-model aimed to develop a structured framework to identify areas of visual conflict and provide a management strategy that can be applied to better understand and to minimize these impacts. The visual capacity sub-model addresses aquaculture's potential visual impact derived from two related distinctive environmental considerations, landscapes and seascapes, combined with viewshed analysis. This assimilation of ecological factors into visual aspects of landscape planning has been discussed previously (Sheppard, 2001: Termorshuizen *et al*, 2007) and the problems encountered are ideally suited to be addressed within a spatial framework linked to GIS.

A Western Isles visual capacity sub-model was developed in order to visually identify high areas in terms of important visual, landscape and seascape areas (Fig. 7.5). This aimed to address the complex issue of visual, landscape and seascape sensitivity to incorporate aquaculture developments. The process implemented a digital elevation model incorporating a variety of pre defined important viewpoints assessed over a range of visual envelope distances to determine the visual sensitivity. Landscape values were addressed by incorporating the defined National scenic areas and Landscape sensitivity modelling (Usher, 2001). The coastal sensitivity was addressed by defining seascapes and their sensitivity to incorporating aquaculture development (Hill et al, 2001). These sensitivity sub models were combined to create a final capacity risk model. This identifies areas that can be termed at high risk from an aquaculture development and this therefore allows conflicts to be prevented before any development begins (Grant, 2006).

The final Western Isles visual capacity sub-model indicates that the Western Isles has 3105km^2 (10% of study area) that is highly sensitive to development in relation to aquaculture structures (indicated by the Red and Burgundy). The areas highly susceptible to environmental degradation from aquaculture development are indicated in the middle isles. While low level susceptibility can be seen in Northern Lewis and South Uist.

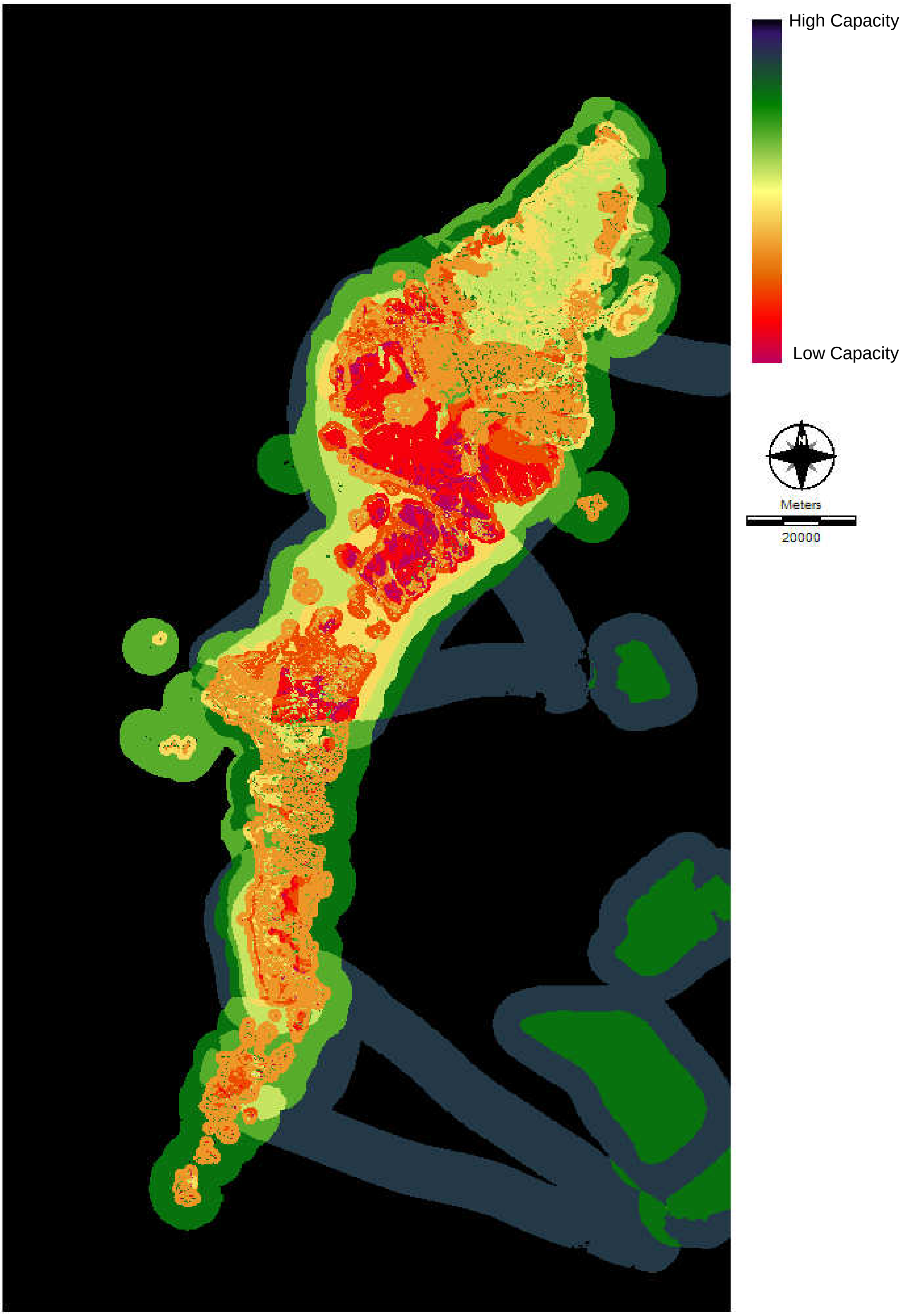

Fig. 7.5 Western Isles visual capacity sub-model.

The legend represents the predicted capacities and associated capacity rankings on a continuous scale from high (extremely vulnerable) to low (least vulnerable).

7.5 Trade-Off Management

All these component sub-models have intrinsic value and can be considered as stand-alone tools generating their own outcomes. However, addressing problems of management of aquaculture development for the Western Isles, or elsewhere, through the combination of sub-models almost certainly requires analysis of trade-offs. Holistic management planning has to take into account all natural, physical, social and economic aspects of the production environment. Berkes and Folke, 1998 identified those linkages such as the fact that those experienced in the development of sustainable aquaculture will often have direct and immediate feedbacks. It is these linkages and feedbacks that need classification and evaluation so that decision-makers can establish all the trade offs that may occur between the components of a holistic model. The Western Isles is highly complex in its natural environment and the multiple users of the environment are in constant competition. When considering aquaculture the main tradeoffs are the interaction with the natural environment which is multifaceted in character.

Trade off analysis is well defined for land use planning and two good representative examples of this are Stoorvogel *et al*., 2004 and Antle *et al*. 2007 who implemented a simulation model called TOA (trade off analysis). This is a modeling tool for an integrated analysis of trade-offs between economic and environmental indicators. Coastal trade off management is most commonly associated with marine protected area management (Brown *et al*., 2001). Trade offs on a very basic level indicate giving up one aspect to increase a different aspect. Not all trade offs are easily ascertained or evaluated. However the trade off here is clearly explicit where the direct benefits from aquaculture productivity and its dependent activities may introduce wastes into the environment thereby degrading the surrounding area and may have visual impact.

Trade off management considers the problem that is under examination (site location for sustainable aquaculture) but also considers trade offs that may be needed to incorporate all aspects of an area (environmental conservation). There is no best solution as aquaculture will very rarely increase the surrounding environmental quality as production increases. The holistic aim is to identify the possible development opportunities for aquaculture while also considering the constraints of the high biodiversity of the area and to find the most appropriate site that considers both values (i.e. trade-off). What must be born in mind is that no single solution will suit all those involved and clearly, when considering trade offs this can only be carried out thoroughly by identification of the competing outputs and involving all relevant parties.

Any decision made cannot avoid a trade-off, choosing one area for aquaculture development will inevitably have a simultaneous impact on its environment. The aim behind the trade off analysis is to identify the more important criteria and values for the area. There will never be a comprehensive union between multiple users and stakeholders so ascertaining a compromise will always be necessary at some level. Achieving these compromises can be assisted by using the tools chosen for the trade off evaluation. Compromises and a thorough understanding of changes that may occur can limit the impact and even mitigate conflicts for the future well being of an area.

There is no one defined appropriate approach to trade off management of different applications. Most successful applications have been applied to forestry management. A detailed breakdown of different methods currently implemented was reviewed by Diaz-Balteiro and Romero (2008). Within the framework of this study, one methodology stands out as the most practical for trade off management within the GIS system, Analytic Hierarchy Process (AHP). AHP can be applied in a GIS context through multi criteria evaluation (MCE) where weights can be applied within an AHP context to reach a decision based on decision-maker preferences. MCE can then be used to explore pairwise weightings and can assign different alternative rankings (Saaty, 1977; Malczewski, 1999; Saaty, 2001) Previous considerations for trade offs with multi criteria evaluations incorporate both quantitative and qualitative indicators and this falls well into the GIS framework which has the capability to carry out these assessments in a very similar way.

Multi criteria decision support can form the basis of a robust decision support mechanism, which is capable of defining a multitude of outcomes determined by the importance of weights attributed to the criteria explored. The main area for compromise will occur when assigning suitable weights for the criteria. The approach to weighting, scoring and ranking through a multi criteria evaluation has to be structured, systematic and easily updated. The framework defined is capable of incorporating a range of views and values in a transparent manner that addresses the problem of identifying best situations where sustainable aquaculture can be developed in the Western Isles.

7.6 Results

There is a multitude of trade-off methods for using and exploring the data from the range of sub-models and their combinations. These are represented here by two approaches, one extracting information and secondly combining the sub-models through AHP. Both are aimed at identifying location-based uses whilst considering the areas that are important on a conservation basis.

7.6.1 Extracting information from the component sub-models

Initial steps for extracting data from the sub-models involved identifying random sample points using capabilities of the GIS (Fig. 7.6) of the two hundred random points sixty three fell within the working area which are representative of areas that may be assessed for an EIA for developing a fish farm site. Structured database query was built around a macro model (see Appendix A1) which incorporates five sub-models, the three cage site suitability sub-models, the biodiversity sub-model and the visual capacity sub-model, and which extracts cell values from the sub-models. The resulting output files are no longer an image but a range of information that can be used for statistical analysis and evaluation (Table 7.1).

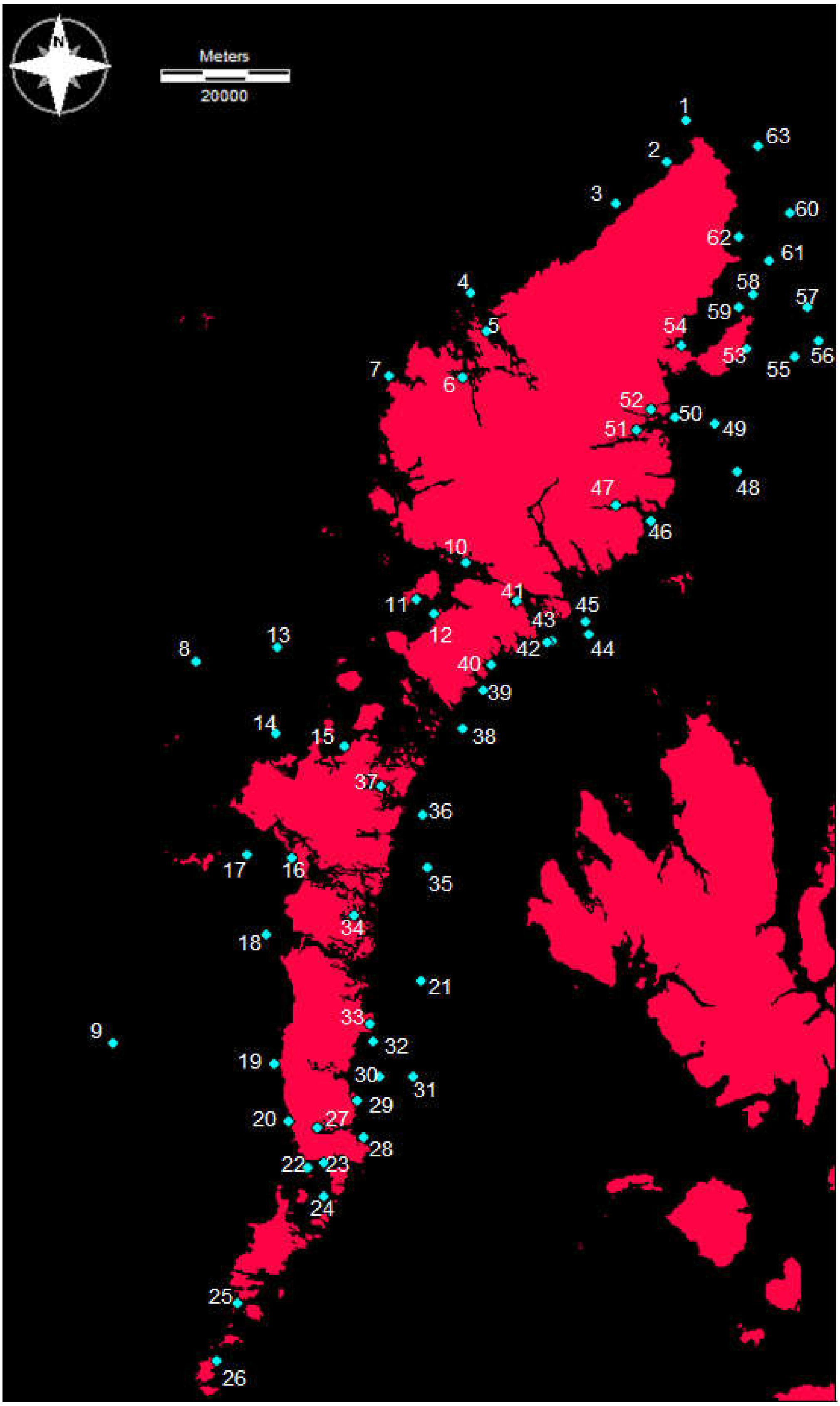

Fig 7.6 Random sample points (Cyan Dots) as generated in IDRISI and used for structured database query.

Table 7.1 Twenty representative query results extracted for the random sample points from the component sub-models in the Western Isles decision support system.

Random Sample Site	LMS Sub-model	C250 Sub-model	C315 Sub-model	Biodiversity Indicators Sub-model	Visual Capacity Sub-model
1	3	6	8	3	4
2	3	9	7	4	5
3	4	9	7	5	3
4	2	4	5	6	3
5	6	8	8	10	7
6	6	8	8	8	8
7	3	5	8	4	6
8	0	0	0	1	0
9	0	0	0	1	0
10	7	8	8	6	8
11	6	8	8	6	8
12	6	8	8	6	8
13	2	5	9	4	0
14	2	5	9	4	4
15	7	6	0	8	8
16	7	6	0	7	6
17	6	8	8	5	4
18	6	8	8	6	3
19	7	6	0	8	7
20	7	6	0	8	7

As a final step, data from the particulate dispersion can be included, thus allowing for identification of areas that are already influenced by particulate dispersion.

7.6 .2 Combining the Sub-models within GIS

The final overall suitability for each of the cage designs first considered trade offs in relation to conservation. This was carried out through a multi criteria evaluation combining the site suitability sub-models with the biodiversity sensitivity sub model and the visual capacity sub-model. For the particular case of the Western Isles, biodiversity sensitivity was weighted higher than the visual capacity in an MCE, although this would not necessarily be the case elsewhere.

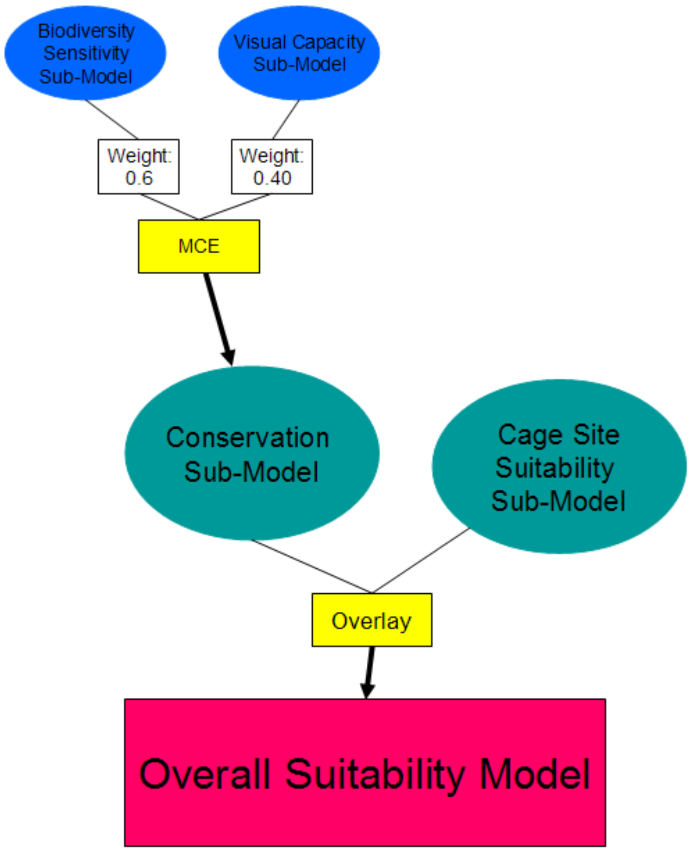

Fig. 7.7. Diagrammatic representation of the combination of Biodiversity Sensitivity Sub-model, Visual Capacity sub-model and Cage Site Suitability sub- models to create the Overall Suitability Model for coastal aquaculture in the Western Isles, Scotland.

The Conservation sub-model (Fig 7.8) identifies the sensitive areas that need to be considered in aquaculture development. This conservation sub-model was combined with the site suitability sub-models through subtractive overlay to create the final usage zones for aquaculture development in the Western Isles. Areas that are most appropriate for aquaculture development are represented by ranks 5 and above, while ranks 4 and below represent less appropriate areas for aquaculture development (Table 7.2) as chosen by the author. The final exploratory step is to overlay the particulate dispersion sub-models with the combined Overall Suitability Model to allow for the identification of areas that are experiencing possible detrimental impacts. This identification ensures that new farms are not located too close together and is a logical separate development which is needed to ensure a minimization of potential cumulative impacts (Perez *et al*, 2005).

Table 7.2 Final combined Overall Suitability Model. Area results km^2.

Category	Cage design		
	LMS	**C250**	**C315**
0	27091	24392	24178
1	1542	1363	1089
2	1760	2407	2505
3	949	1998	1559
4	243	942	1521
5	14	338	366
6	1	152	293
7	0	8	89

The final models indicate that the Western Isles has 748km^2 (2.5% of the whole study area) appropriate for development when implementing the C315 (exposed cages) in relation to aquaculture whilst considering the interactions with conservation areas (Fig. 7.8C). The C250 (semi-exposed cages) overall model indicates that the Western Isles has 498km^2 (1.6% of the whole study area) that is appropriate for development implementing the C250 cage types (Fig. 7.8B). However, further investigation of these areas using the particulate sub-model reveals that these suitable areas are already well exploited. Lastly, cage designs for sheltered environments LMS have very limited scope for development with only 15km^2 (0.04% of the whole study area) being ranked at 5 or above (Fig. 7.8A).

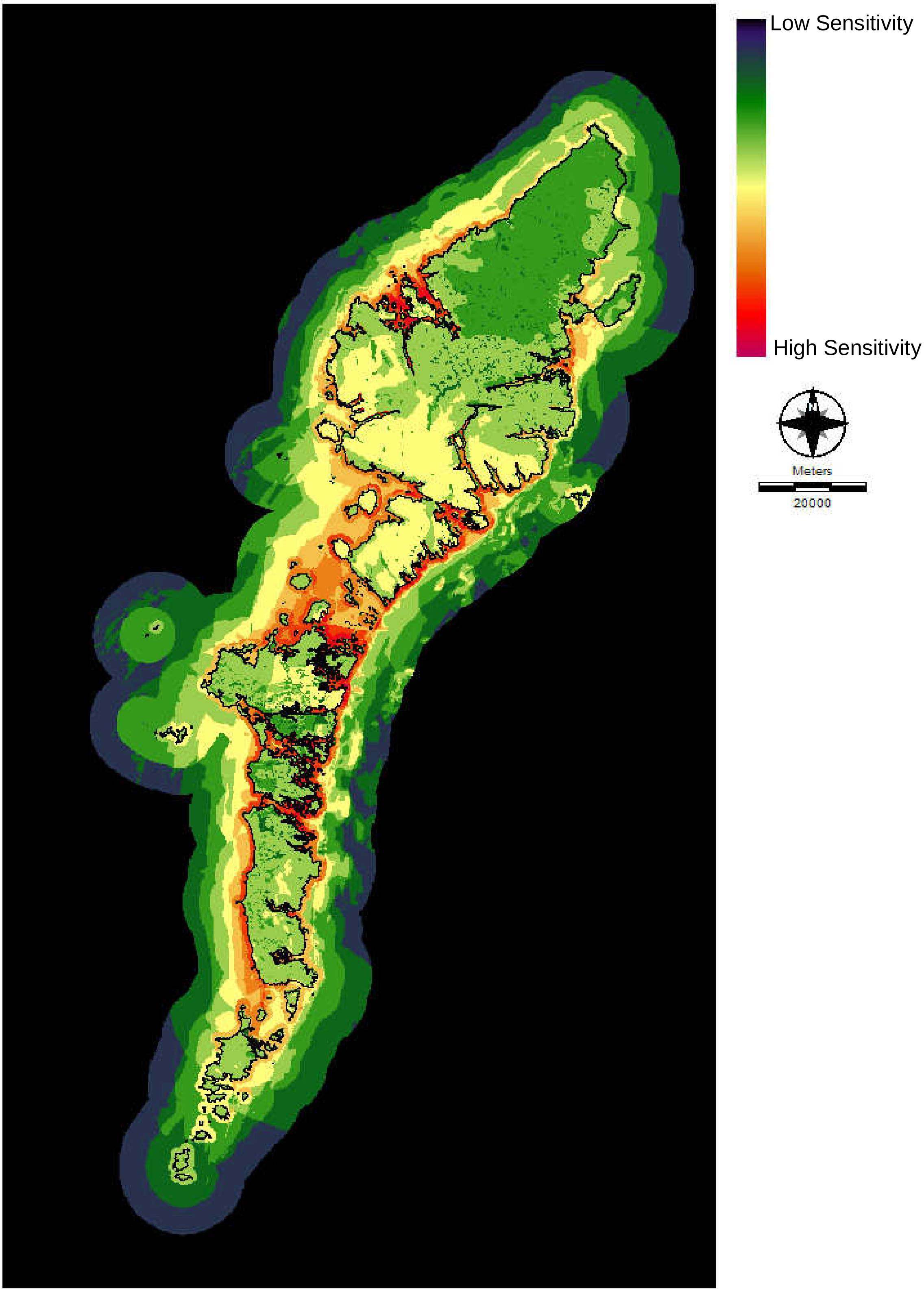

Fig 7.8 Conservation sub-model for the Western Isles.

The legend represents the predicted sensitivity rankings when combining Biodiversity Sensitivity Indicators sub-model and the Western Isles visual capacity model the legend represents a continuous scale from low to high.

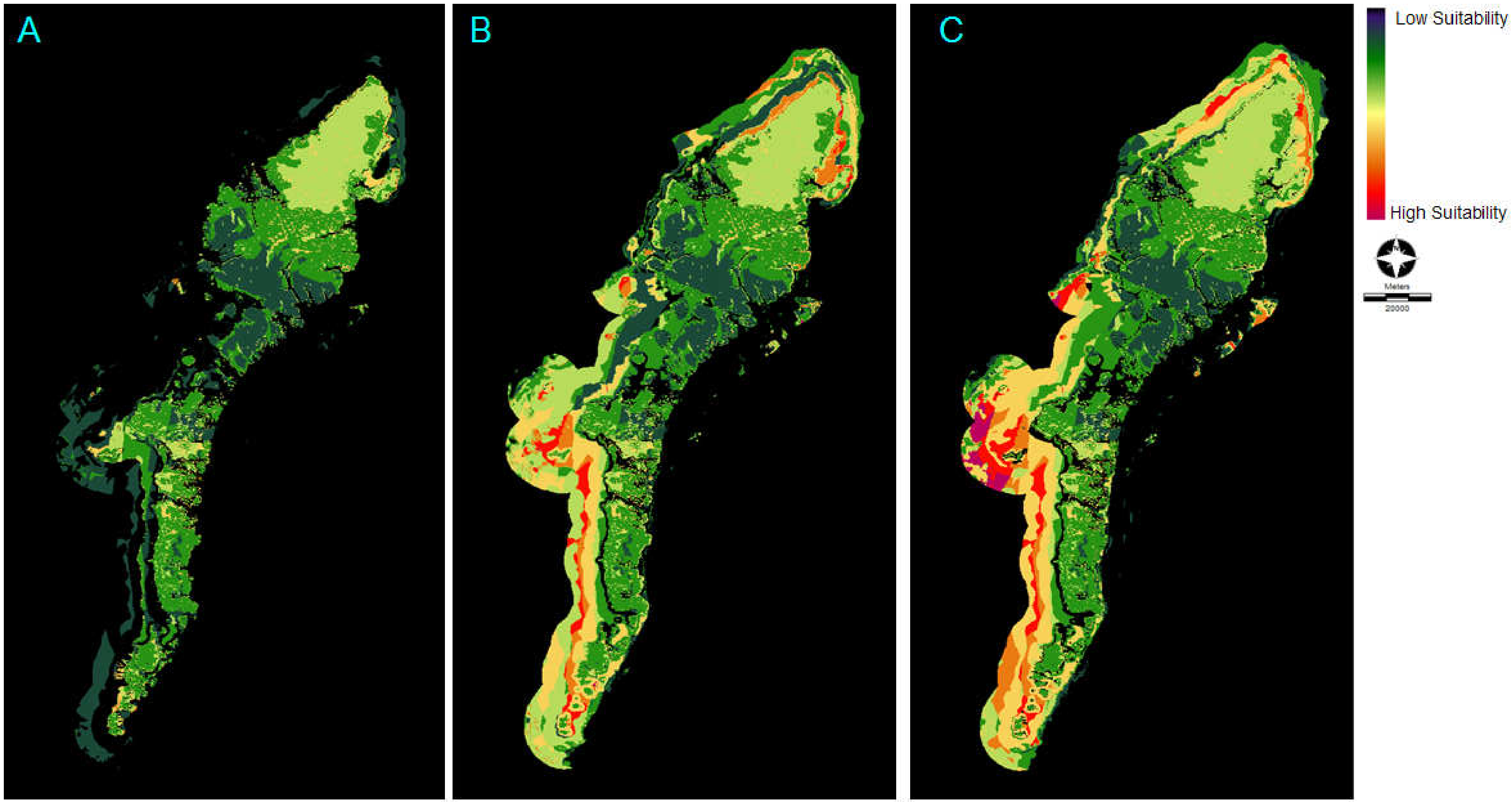

Fig. 7.9 Holistic GIS Model combining Cage Site Suitability sub-models and Conservation sub-model for all three cage types A= LMS (for sheltered environments), B = C250 (for semi-exposed environments) and C = C315 (for exposed environments).

The legend represents the predicted suitability for an area to incorporate new structures and the associated suitability rankings on a continuous scale from low unsuitability to high suitability.

7.7 Overall Results

The two methods employed to integrate the four main sub-models have strengths and limitations.

Extracting information from the sub-models can be applied in a structured manner which can address numerous possible conflicts proactively. This type of combination of sub-models is best applied in the initial exploratory stages of identifying potential locations. The type of decision support tool of extracting information can allow the trade-offs to be identified at a detailed level. The framework is open and transparent which is ideally suited for encouraging all stakeholder and communities to be involved where conclusions reached can be easily communicated to all.

The second method combining the sub-models in an Overall Suitability Model, applied in an Analytic Hierarchy Process also provided a coherent representation of suitable site selection which considers the trade-off with conservation specifics on the Western Isles. Whilst a detailed and queryable image set is presented the end result is specifically restricted to the issue under study. This focused combination of results, although appropriate in the context of this study, would require adjustment in order to be applied in other contexts.

7.8 Discussion

Scotland's current policies for fish cage site selection have been considered to be inadequate and lack the strength to support sustainable development of aquaculture (Scottish Parliament 2002a,b). This study aimed to identify the most suitable and sustainable locations for allocating active marine pen sites in a holistic manner. The analysis considered the site selection, biodiversity sensitivity, important sea/landscape areas and current particulate dispersion from fish farms as the most important components for the Western Isles. While the range of sub-models considered are seemingly incompatible, database integration was achieved within GIS to assess evaluation of the criteria for site selection.

Geographical information systems (GIS) are a strong tool for the spatial analysis of aquaculture management (Aguilar-Manjarrez and Nath 1998; De Graaf *et al*, 2003; Jenness *et al*, 2007). A recent disadvantage of their application is thought to be that complex interactions can be difficult to display in two dimensions (Foden *et al*, 2008), however this was not found to be a limitation in the present study and with GIS software continually developing it is not likely to hinder future studies.

Holistic planning and management for sustainable aquaculture on the Western Isles of Scotland is a multidimensional, intricate environmental issue to address. Two structured and coherent methods were explored which could be highly useful for involving all relevant stakeholders and aid the process of coastal management. The stakeholder and public perceptions of marine aquaculture in the Western Isles have been shown to be generally acceptable (Whitmarsh and Palmieri 2009). However, any level of social acceptability of aquaculture is closely linked to its perceived environmental impact (Katranidis *et al*, 2003, Whitmarsh and Wattage, 2006). Multi criteria modeling and data extraction techniques are decision support tools in GIS that can provide guidance in the planning and development stages for aquaculture activities in a platform which is suitable for universal collaboration from all interested parties. The GIS framework, database query and analytical processes developed here show that holistic management planning is capable of analyzing the range of trade-offs identified by stakeholders and governing bodies. It is a transparent, structured and highly organized tool that can address the perceived environmental impact in a coherent manner.

The ability to create a framework that is clear and easily editable and updateable at any stage, for example by using macro models, is a high-quality process that makes transparent all the underlying assumptions used in the modeling process and identifies issues that need further clarification. This type of framework in implementing a GIS system has been shown to be able to incorporate controlling factors to explore the coastal environment and ensure the application of appropriate management strategies (Rodriguez *et al*, 2009). In such a case the methodology to arrive at the decision must be scientifically sound and transparent in its approach. An optimal solution is always the best option but may not always be achievable. Thus strategies that can identify the relevant trade-off in terms of the conflicting criteria to find a compromise decision are essential.

The complex issues associated with sustainable development sites for aquaculture in the western isles have been discussed above. This work has shown that by extension of the site suitability sub-model it can be demonstrated that it is possible to enable optimal aquaculture developments to take place by providing a framework that allows the minimization of adverse environmental impacts. These models enable environmental managers and regulators to make more informed and objective decisions about location and siting of cages. The Western Isles clearly has opportunities for future aquaculture development and the holistic combined approach outlined in this study offers an option that is likely to increase the environmental benefits to be gained from utilization of a more informed planning process. In summary, the GIS spatial marine modeling provides a highly beneficial structural management tool that can incorporate a number of complex components, typical of those that occur within the Western Isles region and elsewhere.

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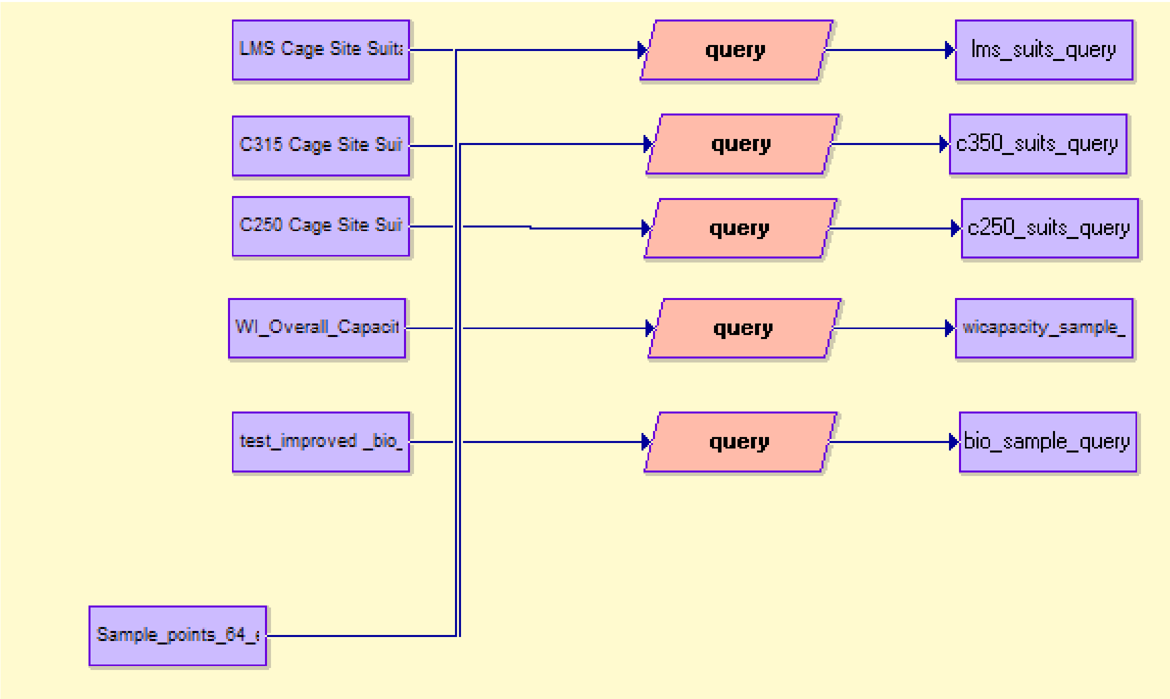
7.10 Appendix: Supplementary figures.

A1. Diagrammatic representation of the macro model used to extract data from the set of sub-models.



A GIS-based decision support tool for optimisation of marine cage siting for aquaculture: A case study for the Western Isles, Scotland.

Chapter 8

8.1 Summary of Conclusions

The current major failures of new aquaculture farms can be found in inaccurate identification of areas as appropriate for aquaculture development (Hossain *et al*, 2009). Defining and determining the appropriate locations for fish cages considering the natural conditions and the needs of the operation and cultured species can be managed successfully through GIS (Halide *et al*, 2009: Mahalakshmi and Ganesan, 2009). The implementation of GIS decision support developed in this study has been shown to be a reliable primary indication of suitable locations which can then be explored further by addressing potential conflicts .The work conducted here has shown that this approach can be taken even further in a multi-faceted holistic model that allows consideration of sensitive environments and incorporates active fish farm information.

GIS models are known to be strong support tools designed to aid the decision making process. However it is possible that this method does not always provide definitive answers to a given problem (Perez *et al*, 2003), principally due to the human and societal aspects of any decision-making process. Within the study presented here it is demonstrated that GIS-based models can successfully manage and manipulate a wide range of datasets that are essential components in the determination of suitable locations for aquaculture. With further refinements, in particular reference to the particulate sub-model, it will be possible to extend this approach to consider multi-site carrying capacity. The framework to sustainable aquaculture presented is open in its approach, considers all relevant agencies and stakeholders and is highly applicable across a range of issues. It is likely that the benefits from use of GIS in this way are applicable not only to aquaculture but to all users of the coastal zone

Whilst ICZM and EAA (Soto *et al*, 2008) presents an integrated and positive approach to the coastal zone, GIS has been shown in this study to be a most effective practical tool for applying these frameworks. GIS can incorporate a vast amount of spatial data, it can visually display analytical and statistical results in a manner that is easily understandable. The greatest strengths of GIS lie in its ability to be predictive and to simulate future scenarios of the coastal environment.

For the Western Isles, this study has shown that it is feasible to consider the requirements and goals for its sustainable development whilst simultaneously having the ability to incorporate the requirements and goals of a variety of other costal zone users.

As the Scottish Government promotes integration of all bodies involved in coastal zone governance (Baxter *et al*, 2008) the study here illustrates the important benefits that can be gained from the harmonized management of information in a spatial database The models presented and developed throughout the study have been demonstrated to be flexible, instrumentally coherent and communicatively balanced in the approach to the management and planning of the coastal environment for its users.

Despite the complexity of this large scale study the results have demonstrated the potential contributions that a GIS framework can make to the issues explored. This framework has also demonstrated the ability to apply a scientific rigour to the highly complex problems of site suitability, biodiversity, landscape capacity and multi site waste dispersion for aquaculture.

In summary, this study has highlighted the importance of promoting an integrated approach for the optimal future development of sustainable aquaculture. It has demonstrated the most appropriate means by which this type of modelling can be utilised to solve existing and future practical aquaculture development problems. One of the major demonstrated benefits of the resulting models is to illustrate a process whereby appropriate areas for sustainable aquaculture development can be identified through utilisation of a GIS frame work which incorporates trade off management. The cumulative findings of this study have shown that:
GIS can be used to evaluate and optimize the location of marine cage systems and can support the decision making process by utilising a more coherent method of Site Suitability modelling. This included:

- Successful development of layers pertaining to important environmental factors relevant to cage designs (wave climate, bathymetric profile and substrate profile).

- The wave climate sub-model has considerable value as a stand-alone tool for numerous applications.

- Combining these layers to form the sub-models indicated that the Western Isles has very restricted development potential for cages designed for sheltered environments (91km^2)

- Demonstrating the limited availability of development potential for cages designed for semi exposed environments (1543km^2).
- Identifying that the optimal potential for aquaculture development is shown with cages designed for exposed environments (3103km^2).
- Utilizing the sub-model as a stand alone item or combined into a larger framework for site selection.
- Highlighting the transferability of the study from the Western Isles to the rest of Scotland's coastline.

Multisite particulate modelling at one metre resolution was shown to be achievable within a GIS framework implementing maximum current velocity as the friction/force image. This sub-model exhibited the following characteristics :

- The ability to incorporate within a macro model a design that could be easily used by stakeholders and governing bodies.
- Demonstration that Loch Skiport and Baghnam Faoileann Fjord Systems outer farms have a larger dispersion pattern in comparison to the farms located in more sheltered areas of the fjord system which display a smaller dispersion pattern.
- The East Benbecula Fjord System indicates a prominent eastern dispersion pattern from all farms within this fjord system.
- Loch Erisort and Loch Leurbost Fjord Systems dispersion patterns showed that the farms in the northern part of the Fjord have a greater dispersion pattern when compared with those in the sheltered south part of the fjord system.
- Loch Roag Fjord System the farms on the Eastern side of the fjord system tend to disperse wastes over a wide area. Those on the Western side of the system are much less dispersive. It should be noted that throughout the fjord system, even where farm sites are close neighbours, there appears to be minimal interaction in the particulate dispersion from these farms.
- The models developed indicated that future developments of this macro model would benefit from the incorporation of some quantitative aspects of the more complex spreadsheet model.

GIS was successfully implemented in evaluating biodiversity sensitivity indicators in terms of Aquaculture activity.

- Successful development of layers pertaining to biodiversity sensitivity indicators in relation to aquaculture activities (Species sensitive to Aquaculture, Endangered species, Species important to the Western Isles and important spawning and nursery areas).

- Several of these sub-model components have value as stand-alone tools for other applications.

- Combining these layers to form the sub-model indicates that the Western Isles has 1168km^2 (4% of study area) which is highly sensitive to aquaculture activity.

- 20595km^2 (65% of study area) has a biodiversity that is much less sensitive to aquaculture.

- The sub-model can operate as a “stand alone” tool or can be combined into a larger framework.

- Little modification and re-parameterisation is required to enable such models to be developed to cover the whole of the Scottish coastline, or any other coastal locations worldwide.

Aquaculture can affect landscapes, seascapes and the visual capacity of different areas can be adversely affected. GIS was successfully applied to investigate this contentious issue.The final sub-model shows that the Western Isles has substantial capacity for aquaculture development. It was shown to be possible to:

- Successfully develop Seascape and Landscape sensitivity analysis in relation to aquaculture structures.

- Apply a novel approach to visual assessment through use of proportional viewshed assessment

- Demonstrate that 6448km^2 (20% of study area) is categorized as having a high capacity to incorporate new aquaculture developments.

- Demonstrate that 3301km^2 (10% of study area) has a moderate capacity to incorporate new aquaculture structures.

- Demonstrate that in 1324km^2 (4% of study area) there is low capacity for new aquaculture development structures.

- Operate the sub-model as a “stand alone” tool or to combine it into a larger framework.

An overall conceptual framework was designed to explore two methods for the combination of all the sub-models detailed above to identify the most appropriate areas for sustainable aquaculture development with major consideration of any possible conflicts with particular reference to conservation issues. Both approaches had strengths and weakness but both showed that GIS is a strong tool for the spatial analysis of aquaculture management. The steps undertaken were:

- First evaluations involved the extraction of information from the component GIS sub-models into a structured database.
- The extracted data provides a range of information that can be used for statistical analysis and evaluation of the optimal siting of aquaculture in the Western Isles.
- The second method involved combining the sub-models within GIS using MCE and considering trade-offs in relation to conservation.
- The GIS combination of sub-models indicated that the Western Isles has 748km^2 (2.5% of study area) appropriate for development implementing the C315 cage for aquaculture whilst considering the interactions with conservation areas.
- The C250 overall model indicated that the Western Isles has 498km^2 (1.6% of study area) as appropriate for development implementing the C250 cage types.
- The model indicated that the LMS cage designs for sheltered environments have highly limited scope for development at only 15km^2 (0.04% of study area).

In conclusion this study has shown that:

- The Western Isles does have scope available for further sustainable aquaculture development.
- The sub-models and frameworks implemented in this study can be replicated for the rest of Scotland, or elsewhere.
- Holistic planning and management for sustainable aquaculture on the Western Isles of Scotland is a multidimensional, intricate environmental issue. It is probably only possible to address this problem adequately through utilisation of a scientifically robust GIS framework.

8.2 References

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