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Tools for Assessment and Planning of Aquaculture Sustainability

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Critical Evaluation and Suggestion of Models

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Please be aware this document may be updated as the critical evaluation continues throughout the TAPAS project (2016- 2020).

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SUMMARY

This report presents an overview of a critical evaluation of near-field models (defined as farm level to water-body scale) currently used for either regulatory or scientific purposes to assess nutrients/wastes. The evaluation was carried out as part of the Tools for Assessment and Planning of Aquaculture Sustainability (TAPAS) project, an H2020 research project running from 2016 to 2020 (www.tapas-h2020.eu). TAPAS aims to promote the sustainability of European aquaculture and alleviate bottlenecks by providing tools for key stakeholders at local, national and EU level. Within the project a series of presently employed and adapted environmental models will be compared to illustrate the most appropriate near field modelling procedures for marine and freshwater aquaculture sustainability throughout Europe, based on carrying capacity and site selection. This critical evaluation is the first stage of that process and provides the foundation for further work within the TAPAS project. The models and tools can contribute to the Environmental Impact Assessment (EIA) process and wider certification schemes and sustainability assessments of freshwater and marine aquaculture throughout Europe.

The report is a formal requirement of Deliverable 5.1, submitted in Month 4 of the project. It provides a foundation for the work that will be conducted in Work Package 5 "Near-field models for regulation and site selection". This critical evaluation will continue throughout the lifetime of the TAPAS project.

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1. Introduction

As the global population continues to grow, aquaculture must increase or intensify production to meet the rising demand for seafood. However, since each aquaculture system demands certain resources not all areas are suitable for production. At the farm or waterbody scale, the sustainability of aquaculture depends on many factors including environmental characteristics, ecological interactions, production strategies and management decisions as well as social and economic considerations. However, even if an area is suitable for culture it may not be available as other activities compete for the same space and resources. There is also a need to maintain biodiversity so certain areas will be unavailable as they are designated for conservation purposes. The location of a farm, and the capacity of the area to support production, is of fundamental importance and must be considered by producers and regulators prior to establishing or expanding a farm.

Carrying capacity is an important concept for ecosystem management and is a major component of the ecosystem approach to aquaculture (EAA), a strategic approach to development and management which aims to integrate aquaculture within the wider ecosystem (Soto et al., 2008; Ross et al., 2013). Broadly speaking, carrying capacity can be defined as "*the level of resource use both by human or animals that can be sustained over the long term by the natural regenerative power of the environment*" (Ross et al., 2013). As noted by Ross et al. (2013) this complements the terms assimilative capacity, "*the ability of an area to maintain a healthy environment and accommodate wastes*" (Fernandes et al., 2001), and environmental capacity, "*the ability of the environment to accommodate a particular activity or rate of activity without unacceptable impact*" (GESAMP, 1986). When considering aquaculture, carrying capacity can be divided into at least four categories; physical carrying capacity, production carrying capacity, ecological carrying capacity and social carrying capacity (Inglis et al. 2000; McKindsey et al. 2006; Gaĉek and Legović, 2010; Ross et al. 2013).

Physical carrying capacity is the suitability of an area for development given the physical aspects of the environment and requirements of the farming system (Ross et al., 2013). It can be used to quantify total potential area available for aquaculture but it provides insufficient information to determine limits (Byron and Costa Pierce, 2013). Thus, it may be considered the initial site identification as it determines development potential but more specific site selection and carrying capacity assessment should follow at a later stage (Ross et al., 2013). Production carrying capacity is the maximum production that can be supported in any given area or location and is normally assessed at farm level (Ross et al., 2013). Is important to note that production carrying capacity is closely linked with ecological carrying capacity. Ecological carrying capacity is the level of production that can be maintained without leading to changes to ecological processes, services, species, populations or communities in the environment (Ross et al., 2013). Finally, social carrying capacity is the amount of aquaculture that can be developed without adverse social impacts. This can include consideration of visual impacts, traditional fishing rights and the needs of communities and other resource users (Ross et al., 2013).

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Assessment of carrying capacity for aquaculture is challenging as there are many different factors that must be considered (Ross et al., 2013). The complex processes involved in and between farms, ecosystems and society are often difficult to measure. In science, models are some of the most powerful tools used for understanding and simulating the interactions between environment, ecosystems, people and animals (Mulligan and Wainwright, 2004). Models are simplifications or substitutions of systems and can be used to predict real or hypothetical scenarios that would otherwise be costly, difficult or even dangerous to perform. Consequently, models are useful tools for predicting impact and can be used for planning, management and regulation, especially during the Environmental Impact Assessment (EIA) process (Glasson et al., 2012).

Many environmental models have been developed to assess the near field issues associated with aquaculture (McKindsey et al., 2006; Munro et al., 2010; Ross et al., 2013), however outcomes often focus on a single attribute and it can be difficult to integrate multiple models within larger decision support systems. Furthermore, the use of models varies throughout the world which results in an inconsistent approach to aquaculture management and regulation. China is the World's leading aquaculture producer, however the application of virtual technology and models here is largely limited to research and few have been used in actual management practice (Zhu and Dong, 2013). On the other hand, in Scotland application of models are a legal requirement of the planning and licensing process for both setting biomass limits and the use of chemicals (SEPA, 2005; SEPA, 2008). Even within Europe there is an inconsistent approach to the use of models to plan and manage aquaculture production.

One of the challenges for regulators and stakeholders is deciding which environmental model is most appropriate to use. Models take many different forms, approaches are diverse and structures vary, even within a specific topic or subject (Mulligan and Wainwright, 2004). Often, there is more than one way to model a system, with no single 'correct' approach. A combination of models may be necessary to obtain a more holistic understanding, while in other cases a very specific single-issue model may be more suitable. There should be a balance between simulating the complexity of a system whilst maintaining some degree of simplicity, at least for the end user. As expected this will involve trade-offs and model developers must consider the wider applicability of their model beyond the academic setting if intended for use in aquaculture planning, management and regulation.

This report is a critical evaluation of near-field models (defined as farm level to water-body scale) currently used for either regulatory or scientific purposes to assess nutrients/wastes. The aim is to compare and evaluate key models that could be used by stakeholders for planning and management of sustainable aquaculture. It must be acknowledged that this report does not contain an exhaustive list of all models and approaches. Instead, the most relevant models for European aquaculture systems have been selected and evaluated critically to highlight their strengths, weaknesses and potential areas for improvement.

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2. Farm scale models for marine fish culture systems

2.1. Marine fish culture systems

In Europe marine fish culture is dominated by Atlantic salmon (*Salmo salar*) production. Norway is the largest producer followed by Scotland, Faroe Islands and Ireland (FAO Fishstat J, 2016). Gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) are farmed in the Mediterranean, primarily in Greece and Spain. Rainbow trout (*Onchorhynchus mykiss*) is also produced in Norway, Denmark and Sweden (FAO Fishstat J, 2016). Other species farmed in marine systems include Meagre (*Argyrosomus regius*), Atlantic cod (*Gadus morhua*), Bluefin Tuna (*Thunnus thynnus*) and Arctic char (*Salvelinus alpinus*).

Although some species may be farmed using land-based systems, most marine fish culture will involve cages. Due to their design, cages are intrinsically linked with the surrounding area, thus aquaculture can impact, and be impacted by, the environment and other activities. Aquaculture wastes (uneaten food and faeces) will be released directly into the environment, potentially leading to a build-up of nutrients which may affect water quality and sediment chemistry (Beveridge, 2004). Activities, on land and in water (including agriculture and industry), can also contribute nutrients to the environment and cumulative impacts can occur if several farms and/or other nutrient exporters are located in the same area. Thus, it is in the interests of farmers, regulators and other stakeholders for such impacts to be managed. Effective planning and management strategies will need the support of predictive models so the risk of impact can be identified and production licences granted/adjusted/denied using the information.

2.2. Models

At the farm scale, models are used by some regulatory bodies and consultants to assess potential impact from a farm. In Scotland, use of AUTODEPOMOD (a simplified version of DEPOMOD) is a mandatory part of the Scottish marine fish licensing application process (SEPA, 2005). AUTODEPOMOD is also considered a "*credible and robust system*" for predicting benthic impacts as part of the Aquaculture Stewardship Council (ASC) Salmon standards (ASC, 2012). In Norway, AncylusMOM is a legal requirement (Lundebye, 2013). In addition to the regulatory models there are other models that are used for academic and/or management purposes.

2.2.1. DEPOMOD

DEPOMOD [SAMS, Oban, UK] is a waste dispersion model that can be used to assess the potential impact of a cage farm throughout the production cycle and/or predict the impact of a change in biomass (Cromey et al., 2002). There are several components within the model; grid generation, particle tracking, resuspension and benthic response (Figure 2.1, described in Cromey et al., 2002). The grid generation module uses input data (bathymetry, cage and sampling station positions) to generate the sea bed depth array that is used by the particle tracking module. The Langrangian

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particle tracking model considers the release of particles from the fish cages, through the water column and onto the sea bed. The resuspension module is a compartmentalised model consisting of erosion, transport, deposition and consolidation components. The benthic response model predicts two benthic indices (Infaunal Trophic Index and total abundance) for a particular level of solids accumulation. DEPOMOD model also contains two sub-modules; GaBoM (Fish Growth and Biomass Model) for modelling farm biomass and a sub-model for modelling the dispersion of in-feed sea lice medicines.

The Scottish Environment Protection Agency (SEPA), the environmental regulator in Scotland who are responsible for granting marine fish farm licences, contracted SAMS to develop AUTODEPOMOD. This is a simplified version where DEPOMOD and ancillary components are controlled from one single application and with a minimal amount of dialog input (SEPA, 2005). As it was designed to streamline the modelling process, AUTODEPOMOD is less flexible than DEPOMOD. SEPA note there are concerns about the use of the model at very high energy sites and large biomasses, thus the maximum size of any farm that SEPA will consent using AUTODEPOMOD is 2500 tonnes (SEPA, 2005). A new version of DEPOMOD is in development and will be released in late 2016.

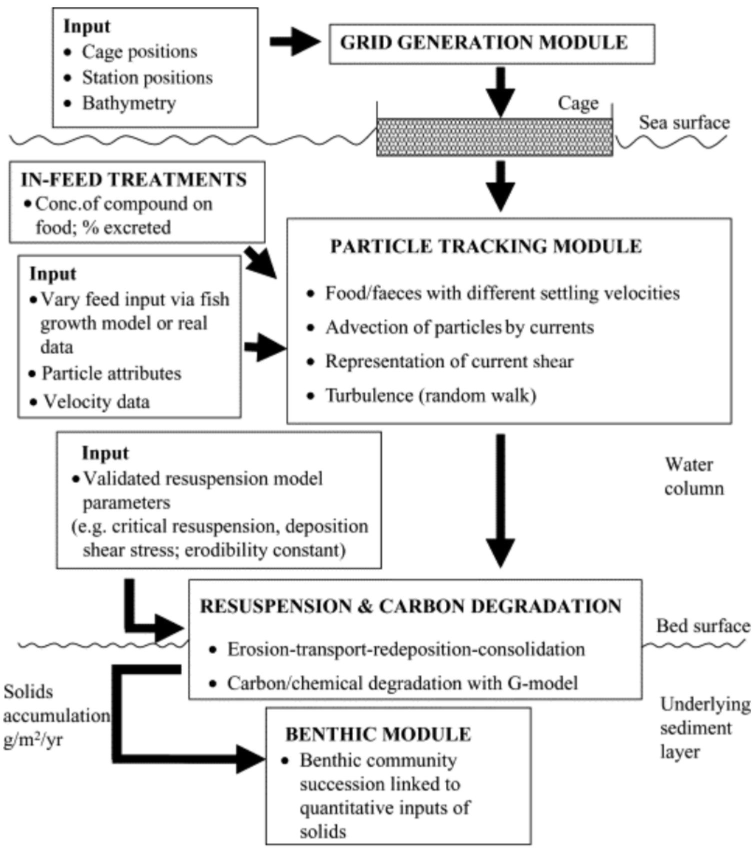

Figure 2.1: Overview of the DEPOMOD modules (Cromey et al. 2002)

Although DEPOMOD was originally developed for Atlantic salmon (*Salmo salar*) in Scotland, DEPOMOD is now used as part of the Aquaculture Licence application process in British Columbia, Canada (Government of Canada, 2014). It is also used commercially by consulting companies in many other countries, including Chile (Garigulo, 2007 cited in Scott, 2013). Cromey et al. (2009) state that physical processes within the model (e.g. particle advection), which are not species specific, do not need to be re-validated. However, Chamberlain et al. (2007) suggested the use of fixed parameters that are "hard coded" into the model may not be appropriate for all sites. The resuspension module uses a fixed critical resuspension velocity (the near-bed current speed that is required to resuspend particles) of 9.5cms^{-1} but a range of critical resuspension threshold velocities have been reported in literature from 0 - 50 cms^{-1} (Chamberlain et al., 2007). Thus, the value used in DEPOMOD may not reflect site conditions and the actual amount of waste that will be resuspended.

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There are other parameters used in DEPOMOD that are "hard-coded" and cannot be changed, many of which are based on assumptions for field data for specific areas.

Although users cannot change parameters, the developers have modified DEPOMOD for several different species and areas. The particle tracking module was re-parameterised using data for cod (*Gadus morhua*) to produce CODMOD and used to assess waste dispersion at a cod farm in Scotland (Cromey et al., 2009). When DEPOMOD was tested on aquaculture sites in the Mediterranean, the model under-predicted the deposition and benthic impact from the cages (Cromey et al., 2012). This highlights the importance of re-parameterising the model with species-specific measurements. Settling rates of faecal material from gilthead sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) were obtained from Magill et al. (2006) and included in the adapted version, MERAMOD (Cromey et al., 2012). However, the settling velocities reported by Magill et al. (2006) were much lower than those found by Piedecausa et al. (2009). As discussed by Piedecausa et al. (2006) many variables can affect the settling velocity which is difficult to estimate.

As large numbers of wild fish aggregate near Mediterranean fish farms feeding on waste material, a wild fish module was included in MERAMOD based on observations at individual sites to account for nutrients removed from the environment by the wild fish (Cromey et al, 2012). Inconsistency in estimating wild fish, and nutrient removal, will lead to errors. However, no clear guidance is provided in Cromey et al. (2012) on how to measure consistently across numerous sites and there is insufficient information on how to account for fluctuation of fish populations and seasonality. Thus, the suitability of the model for regulatory purposes needs further investigation. Although not a formal requirement of the planning process in Greece, the MERAMOD model is used for environmental impact assessment and spatial planning studies. DEPOMOD has also been adapted for the tropics as TROPOMOD where it has been used to assess milkfish and tilapia farms in The Philippines (White et al., 2013) and it has also been revised to model biodeposition from suspended shellfish culture, Shellfish-DEPOMOD (Weise et al., 2009). However, for TROPOMOD in particular there is a lack of information in published literature on the adapted model structure and re-validation of DEPOMOD for freshwater lakes.

Table 2.1: Overview of DEPOMOD

Strengths	**Limitations or weaknesses**
+ Used by several regulators and recommended by ASC certification standards + Has been adapted by the developers for several other species and systems (MERAMOD, CODMOD etc) + AUTODEPOMOD is a simplified version that includes DEPOMOD and ancillary components within the same application.	- Does not consider far field impacts - As the model is hard-coded there are parameters that cannot be changed by the user - Some of the assumptions and values used may not be suitable for all areas.
Summary: DEPOMOD is one of the most popular waste dispersion models used for aquaculture and is used by some regulators. SAMS are currently in the process of developing a new version of DEPOMOD that should be available in late 2016.	

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2.2.2. AncylusMOM

Modelling-On growing fish farms-Monitoring (MOM or AncylusMOM) (http://www.ancylus.net/) is a management system which has two components: Monitoring and Modelling (Ervik et al., 1997; Stigebrandt, 2011). The monitoring programme consists of routine measurements of standard variables to describe the impact of aquaculture on the environment (Ervik et al., 1997), the primary focus in benthic impact and the overall purpose is to ensure there is no violation of any Environmental Quality Standards (EQS) (Stigebrandt, 2011). The model is a web-based planning tool, produced by Ancylus, that can be used to simulate the environmental impact of a farm at a given site and determine management procedures that prevent the impact exceeding environmental quality standards (EQS) for existing farms and new developments (Ervik et al., 1997).

MOM contains four sub-models: fish sub-model, dispersion sub-model, sediment sub-model and water quality sub-models (Stigebrandt, 2004). As shown in Figure 2.2, and described in Stigebrandt (2004), the local model is linked to a regional water quality model, FjordEnv (Aure and Stigebrandt, 1990). The AncylusMOM model and sub-models are described in detail in several publications (Ervik et al., 1997; Stigebrandt, 2004; Stigebrandt, 2011) The fish sub-model calculates the metabolism, growth and feed requirement of the fish and can be used to optimise the feeding regime, maximise growth and minimise wastes (Stigebrandt et al., 2004). The dispersion sub-model uses current variability and estimated sinking time to simulate dispersion and sedimentation rates of wastes (Ervik et al., 1997). This is a different approach to DEPOMOD which uses a particle tracking method (Cromey et al., 2002). The benthic model calculates the oxygen transport to the benthos and then determines the maximum loading with organic matter that permits living benthic fauna (Stigebrandt, 2011), thus estimating ecological carrying capacity (Jusup et al., 2009). The fish cage water quality model calculates minimum oxygen and maximum ammonium concentrations (Stigebrandt, 2004).

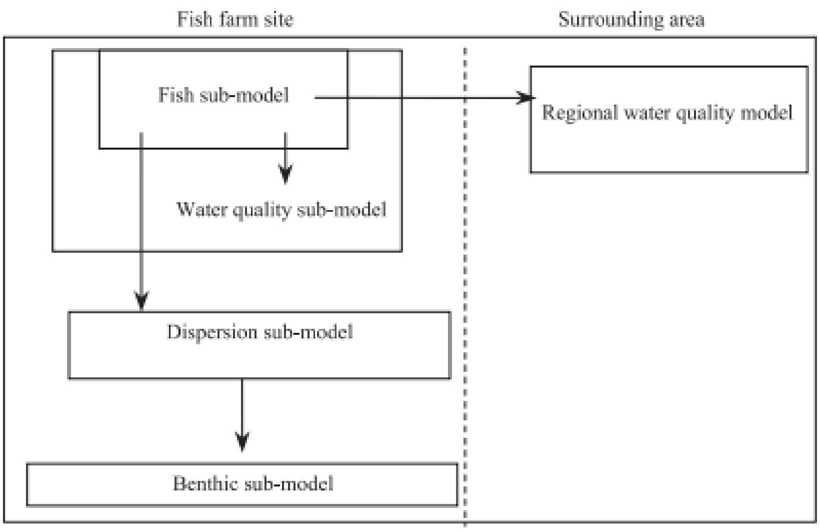

Figure 2.2: Overview of the sub-models in AncylusMOM (Stigebrandt,

The system was designed for Norwegian aquaculture and is legally required by the Directorate of Fisheries as part of the site selection process for salmon and trout farms (Lundebye, 2013). The Norwegian Ministry of Fisheries and Coastal Affairs is integrating MOM into a cohesive management system - MOLO (MOm-LOKalisering) (environmental monitoring - location) to determine where farms should be located, how big they can be and how they should be managed (Norwegian Ministry of Fisheries and Coastal Affairs, 2009; Lundebye, 2013). MOM has also been used to assess intensive

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marine shellfish and seaweed farming in China, although further studies are required to adjust the system for local conditions (Zhang et al., 2009).

Table 2.2: Overview of AncylusMOM

Strengths	Limitations or weaknesses
+ Software runs online by web interface and requires very little time to run + Can be used to assess ecological carrying capacity + Is a management system that includes modelling and monitoring. + Used by regulators in Norway	- Highly simplified treatment of the physical environment and water column biogeochemistry - There is a simple benthic submodel but no explicit treatment of sediment biogeochemistry and return fluxes of nutrients from the sediments to the water column.
Summary: AncylusMOM is different to other approaches as it is a management system that includes modelling and monitoring. It is used by regulators in Norway and has been revised over many years.	

2.2.3. CADS_TOOL

A simplified version of MOM (SMOM) was developed and integrated into a decision support system called Cage Aquaculture Decision Support Tool (CADS_TOOL) for use in South East Asia (Halide et al., 2009). CADS_TOOL is divided into four modules; site classification, site selection, holding density and economic appraisal. The site classification module classifies a site into poor, medium and good suitability based on a selection of criteria and sub-criteria. The site selection model determines how suitable each potential site is by combining the classified criteria and sub-criteria using a multi-criteria analysis based on the analytical hierarchy process (AHP) to produce an overall score for each site. A similar process is often used in the development of spatial models for aquaculture site selection (e.g. Giap et al., 2005; Ross et al., 2011). The holding density module calculates the maximum permissible fish biomass in the cage using SMOM, two oxygen budget models for marine cages (Tookwinas et al., 2004; Hanafi et al., 2006) and a phosphorus budget model for freshwater cages (Pulatsü, 2003). The final module is an economic appraisal and calculates the break-even price and return on investment so can be used to assess the potential economic viability of a farm. CADS_TOOL is a good example of a decision support system that integrates production, environmental and socio-economic factors in a simple, easy to use framework with a user interface. This is advantageous for stakeholders who may not have the necessary scientific background or knowledge required to operate some of the more complex models.

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Table 2.3: Overview of CADS_TOOL

Strengths	Limitations or weaknesses
+ Simple, easy to use framework with a user interface	- Not used widely
+ Integrates production, environmental and socio-economic factors	- May be over simplistic and ignores the complex factors associated with aquaculture production
+ Developed as a decision support tool for stakeholders	- Does not have a spatial output
Summary: CADS_TOOL is a decision support system that integrates production, environmental and socio-economic factors within a simple framework.	

2.2.4. CAPOT model

Cage Aquaculture Particulate Output Transport (CAPOT) (Figure 2.3) is a spreadsheet based model that can be used to predict the dispersion of solid waste materials entering the environment from fish cages (Telfer et al., n.d). The model uses production information and site specific hydrographic data in addition to a number of empirically derived measures or assumptions to calculate the amount and form of nutrients entering the environment from the cages. A sectoral system based on the speed and direction of water currents is then used to model the movement of waste after release from the cages.

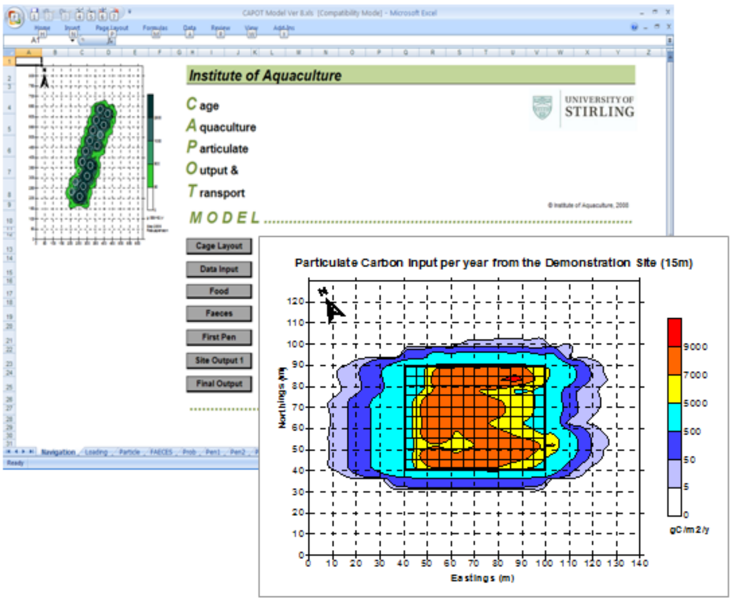

Fig 2.3: User interface of the CAPOT model and example output

The CAPOT model is the result of several studies by a number of investigators. The basic principles of which have been developed in two approaches: spreadsheet based (Telfer, 1995) and GIS-based (Perez et al, 2002; Corner et al, 2006).

CAPOT is the spreadsheet model comprising of two spreadsheets, one for pre-processing of hydrographic data and the other for calculation of waste outputs and distribution. There is also the option to calculate the amount of resuspended material over the modelled time. However, the model assumes the resuspended waste is transported from the area so it may underestimate waste concentrations in sediments close to the cages if the area is hydrodynamically benign (Telfer et al., nd.) The final output can be imported into contour plotting software Surfer^{TM} [Golden Software Inc, USA) and can be converted into spatial layers for use in Geographic Information Systems (GIS). In GIS

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software the CAPOT output can be reclassified into categories or zones based on potential environmental impact allowing easier interpretation by regulators and stakeholders. Furthermore, it can also be combined with other spatial layers in a site selection or environmental impact model and used for decision support in planning and management.

Unlike DEPOMOD and Ancylus-MOM, CAPOT has not been designed specifically for biomass calculation within the environmental parameters and quality standards defined by national regulators, however with some consideration it can be used for that purpose (Telfer et al., n.d.). As discussed by Oliver (2008), although the model is less complex, there are several advantages of CAPOT over DEPOMOD. CAPOT uses spreadsheets so data can be entered quickly and the model is easy to run. This also allows parameters, functions and outputs to be adjusted easily. Consequently, CAPOT is a more efficient and flexible research tool and can be adapted quickly and applied to other study areas and species. First developed for salmon cages in Scotland, CAPOT has also been applied to a cod (*G. morhua*) farm in Shetland, Scotland (Oliver, 2008), fish cages in Huangdung Bay, China (Ferreira et al., 2008a), meagre (*Agyrosomus regius*) cages in the Mediterranean and tilapia (*Oreochromis niloticus*) cages in Lake Volta, Ghana.

Table 2.4: Overview of the CAPOT model

Strengths	**Limitations or weaknesses**
+ Spreadsheet based so can be adjusted easily. + Quick to run and does not require a lot of data. + Has a spatial output that can be imported into GIS.	- May oversimplify hydrographic and benthic processes. - An academic tool rather than regulatory at present.
Summary: CAPOT is a simple spreadsheet based model that can be easily adjusted for new areas and species, and test different production scenarios/practices and consequent environmental impacts. It is not as complex as DEPOMOD and MOM and has not been designed for a specific regulatory system, but it could be adapted for regulatory purposes.	

2.2.5. KK3D

KK3D is a three-dimensional particle tracking model that can be used to predict the benthic carbon loading from fish farms (Jusup et al., 2007; Jusup et al., 2009). The model was originally developed and validated for sea bass and sea bream farms in the Adriatic Sea. The particle tracking technique uses a Lagrangian approach, consistent with the semi-empirical advection-diffusion equation (Jusup et al., 2009; Brigolin et al., 2014). Jusup et al., (2009) note that the use of this approach within the model is important if detailed structure of turbulence in the environment is taken into account in the future. Thus the model could be used for high energy sites, something that may be important if aquaculture systems move to more exposed locations. However, as acknowledged by Jusup et al. (2009) the model should only be used for local scale assessment as inadequate results may be produced further away from the cages. Furthermore, the model is very sensitive to bathymetry (Jusup et al., 2007) so there is a need for detailed bathymetric data. Nevertheless overall data

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requirements are relatively simple and easy to collect for a site: daily fish feed allowance, measured current, cage arrangement and bathymetry (Jessup et al., 2009).

The KK3D model has been used in Environmental Impact Assessment studies in Croatia (Jusup et al., 2007) and more recently, has been integrated with other models. Brigolin et al. (2014) used KK3D together with two individual-population dynamic models for seabass and seabream (based on Brigolin et al., 2010) and a steady-state benthic model (Brigolin, 2009) in an integrated approach to model biogeochemical fluxes at a Mediterranean fish cage farm. Thus, in addition to waste dispersion the integrated model also considers carrying capacity and can be used to assess the suitability of an area for culture and define production limits.

Table 2.5: Overview of KK3D

Strengths	**Limitations or weaknesses**
+ Requires a relatively simple dataset **+** Used in EIA studies in Croatia + Can be used for high energy sites, open ocean aquaculture	- Uncertainty in results further away from fish cage - Only considers particle distribution but can be coupled to other models to evaluate carrying capacity
Summary: KK3D is a particle tracking model that has been used to assess carbon loading from fish farms in the Adriatic sea. It can be coupled with other models to evaluate carrying capacity.	

2.2.6. AWATS

The Aquaculture Waste Transport Simulator (AWATS) is a mathematical modelling package that simulates the physical dispersion of finfish aquaculture wastes for regulatory purposes (Dudley et al., 2000). Whereas the previous models have been developed for European cage culture, albeit in different locations and/or species, AWATS was applied to aquaculture sites in Maine, New England, USA. AWATS links the waste program TRANS, the graphical interface SMS and the flow model DUCHESS, although another flow model can be used if DUCHESS in unavailable for a study site (Dudley et al., 2000). TRANS is a model developed at the University of Maine to simulate advection and dispersion of aquaculture wastes (Panchang and Newell, 1997; Dudley et al. 2000). While DUCHESS is a finite-difference model developed at Technical University Delft, the Netherlands, and used for two-dimensional tidal and storm surge computations (Booij, 1989; Dudley et al., 1998; Dudley et al., 2000).

AWATS was designed as a regulatory tool, hence the addition of the GUI and the graphical outputs that are easy to interpret. Dudley et al. (2000) suggested that further work could incorporate benthic oxygen demand into the framework as this would provide an additional level of decision support. Although AWATS appears to be a promising tool for aquaculture management and regulatory purposes there are no records of application in literature after Dudley et al. (2000). This highlights a

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common issue where models are developed and described in scientific articles but are difficult to access in reality or not supported beyond a project end date.

Table 2.6: Overview of AWATS

Strengths	Limitations or weaknesses
+ Links a hydrodynamic model to a waste dispersion model in one package + Developed as a user-friendly modelling package	- Not used widely - No record of recent use
Summary: AWATS was designed as a regulatory tool, integrating a particle tracking model with a hydrodynamic model and a gui, however there is limited information available and it is unknown if it is still used.	

2.2.7. Other models

Due to the high flushing rates associated with marine coastal areas, most studies focus on modelling the impacts of fish cages on the benthos rather than the water column (Beveridge, 2004). Thus many farm level models have been developed to access particulate waste. However, nitrogen is a limiting nutrient in marine waters so excessive loading can lead to eutrophication (Ryther and Dunstan, 1971). In Scotland, a simple box model is used to estimate the Equilibrium Concentration Enhancement (ECE); the enhancement of dissolved nitrogen, the limiting nutrient in sea lochs, above background levels (Beveridge, 2004) (Equation 2.1). The approach is described by Gillibrand (2002) and has been applied to all Scottish sea lochs with active fish farms enabling an estimation of the relative ranking of environmental pressure on each lochs (Amundrud et al., 2009).

$$\mathrm{ECE} = \frac{\mathrm{SM}}{\mathrm{Q}} \qquad \text{[Equation 2.1]}$$

Where:

ECE is the equilibrium concentration enhancement (kgm^{-3} but converted to µmol^{-1} as ECE measurements are traditionally presented in this format)
S is the rate at which nutrient nitrogen is discharged (kgt^{-1})
M is the total consented biomass of all farms in a sea loch
Q is the flushing rate of the loch (m^{3} per year)

The model uses an annual average for nutrient input, ignoring the variability through the production cycle and assumes that the nutrient nitrogen concentration from aquaculture wastes is conserved with no uptake by primary production (Amundrud et al., 2009). As noted by Amundrud et al. (2009), this is not realistic, particularly in summer months, however the ECE is used as a ranking tool rather than to predict nutrient concentration and the use of seasonal information would not change the overall ranking of lochs. Nevertheless, the addition of seasonal nutrient information could provide useful guidance for monitoring (Amundrud et al., 2009). Amundrud et al. (2009) also suggest that the model is not suitable for non-salmonid species as there are different nutrient loading patterns

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from, for example a halibut (*Hippoglossus hippoglossus*), compared to a salmon (*S. salar*). Consequently, if there are multiple species farmed in a loch then the model is not necessarily suitable for use.

The ECE model is used for semi-enclosed systems such as sea lochs but is not suitable for open water. Another model, described in detail by Gillibrand (2006), is used to determine ECE in open waters in Scotland. The model has been developed in Matlab© and requires data on velocity and nutrient input parameters, either as single balues or time series (Gillibrand, 2006). Gillibrand (2006) notes the model is driven by data that is collected in accordance with environmental impact assessment requirements. Thus, there should be no extra data collection for stakeholders. The model considers water exchange in the near field region, typically the same area as the tidal excursion (Gillibrand, 2006). However, this is a very simplistic approach and may not be suitable for dynamic environments.

There are other models that are used at the farm scale to assess carrying capacity and environmental impact. A popular commercial model is The Farm Aquaculture Resource Management (FARM) (www.longline.co.uk), was originally developed for shellfish (Ferreira et al., 2007) (and a more detailed overview is provided in Section 4 of this report), however it has been adapted for several fish species; Atlantic salmon (*S. salar*), Rainbow trout (*O. mykiss*), Gilthead seabream (*S. aurata*), European Seabass (*D. labrax*) and Nile tilapia (*O. niloticus*). FARM combines physical and biogeochemistry models, growth models and screening models for determining production and assessing eutrophication (Ferreira et al., 2007). The FARM model uses a simple dataset of information that is usually monitored by stakeholders. Outputs include deposition analysis, dissolved oxygen and sediment oxygen demand analysis, water quality impacts and assessment of nutrient input in the water body (Longline, 2016).

2.3. Integrated multi-trophic aquaculture (IMTA)

With space at a premium and a need to reduce the environmental impacts from aquaculture, Integrated multi-trophic aquaculture (IMTA) is considered a way of recycling waste nutrients for economic gain as fed fish, inorganic extractive species and organic extractive species are grown together (Troell, 2009; Chopin et al., 2012; Granada et al., 2015). For modellers, IMTA presents a challenge as there will be multiple species to model compared to a single species in monoculture, and each species interacts with the environment (and each other) differently. Consequently, there are complex nutrient cycles within the farm and also between the species, system and the wider ecosystem which can be difficult to simulate.

Although IMTA is a relatively new term, the concept is based on the polyculture technique that has been practiced for many years in China and other Asian countries. Models have been developed and used to assess polyculture in marine systems, for example, Nunes et al. (2003) developed a multi-species model for shellfish polyculture (Chinese scallop *Chlamys farreri*, Pacific oyster, *Crassostrea gigas* and kelp *Laminaria japonica*) in a coastal bay in China. However, modelling marine IMTA systems includes additional processes as finfish are also included so there will be feed inputs and waste outputs from the fish to consider. Ferreira et al. (2012a) used the FARM model to simulate

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production and environmental effects of gilthead bream (*Sparus aurata*) in monoculture and IMTA with Pacific oysters (*C. gigas*). An individual fish growth model based on net energy balance was developed and integrated with the existing shellfish models in FARM (Ferreira et al., 2012a). A similar approach was also used to model the production and environmental impact of nile tilapia (*Oreochromis niloticus*), white shrimp (*Penaeus vannamei*) and the green seaweed *Ulva,* for several different scenarios in Thailand (Ferreira et al., 2015).

Several studies have developed multi-trophic models for marine IMTA systems to assess production and nutrient flow. Ren et al. (2012) developed a generic IMTA model for finfish-shellfish-detritivore-primary producer systems and the model was parameterised and tested using potential IMTA species; salmon, mussels, sea cucumbers and seaweed. Lamprianidou et al. (2015) constructed a model that determines the nutrient recovery efficiency and production biomass of an IMTA system and based on growth models. The model was parameterised using Atlantic salmon (*S. salar*), sea urchin (*Paracentrotus lividus*) and seaweed (*Ulva* sp.) data, although similar to the model developed by Ren et al. (2012), the model developed by Lamprianidou et al. (2015) can also be re-parameterised for other species. Lamprianidou et al. (2015) focussed on a virtual closed system, however there is potential to couple the model to waste dispersion models and evaluate an open system. This would be useful for site selection and carrying capacity studies.

Using MIKE3-ECOLab (https://www.mikepoweredbydhi.com/products/eco-lab), DHI modelled a full-scale IMTA installation where nutrient release from a 2,500 tons rainbow trout farm were sought compensated by growing and harvesting seaweed and mussels to balance the nutrient loss from the fish farm (Plesner et al. 2015). Scenario modelling was used to examine different sites for mussel and seaweed farming. Within the 4-year test period the projected nutrient compensation efficiency was not reached partly due to sub-optimal farming sites which was confirmed in hind-cast modelling.

2.4. Strengths and weaknesses

Many farm scale models focus on particulate waste distribution and impact on the benthos rather than the water column as marine sites normally have high flushing rates (Beveridge, 2004). One of the weaknesses of all particulate tracking models is the resuspension module or component. Few models consider all complex biogeochemical processes in degradation and often use a simple half life degradation equation. In simple models resuspension can be difficult to simulate so DEPOMOD, and other models, use a fixed current speed value to determine when particles would be suspended. However, as noted by Chamberlain et al. (2007), this may not be suitable for all sites and may overestimate the amount of re-suspended waste, thus underestimating the impact under the cages. Many farm scale models use fixed parameters so they are simple to operate, however it also makes application to other systems, species and areas difficult.

AncylusMOM is an interesting approach as it includes both a modelling and monitoring component as part of a larger management system. This is useful for regulatory purposes as it is a clear framework that is easy for decision makers to understand and work with. Furthermore, the model is easily coupled to a waterbody model (FjordEnv) enabling consideration of wider field effects.

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However, both AncylusMOM and FjordEnv are simple models and may not be suitable for more complex systems.

Models do not necessarily have to be developed using a programming language. Lamprianidou et al. (2015) used the visual simulation package Powersim^{TM} Constructor Studio 8 [Powersim Software AS, Bergen] to develop the model. Such modelling software packages are particularly useful for modelling nutrient flow through complex systems such as IMTA as they can be updated quickly and re-parameterised easily as highlighted by Lamprianidou et al. (2015). There are several modelling packages available that can be used to construct simple or complex dynamic models such as Stella [isee systems, Lebanon, NH, USA], Vensim [Ventana systems inc, Harvard, MA, USA] and Powersim [Powersim Software AS, Bergen]. A number of popular aquaculture models have been developed using these models including ShellSim which was developed in Stella (Hawkins et al., 2013) and various components of FARM were developed and tested in PowerSim and Stella (Ferreira et al., 2007).

2.5. Summary and recommendations for models

DEPOMOD and Ancylus-MOM are both used for regulatory purposes in European salmon aquaculture. As Scotland and Norway have similar culture techniques and environmental conditions a comparison of the two approaches would be useful to understand the similarities and differences. This is not only useful for Scotland and Norway to determine if aquaculture is being regulated in a similar way in each country, but it will also benefit other countries that use, or are considering, either model (or comparable approaches) as a regulatory tool. However, as discussed here, both models are "locked down" and users are unable to change certain parameters. A more flexible approach is the use of spreadsheet models like CAPOT, however the model should also be compared to the previous models as it is simpler so may not be as robust if used for regulatory purposes.

Although it is a popular research topic, there are few examples to date of commercial IMTA systems in Europe (Hughes and Black, 2016). However, with interest growing, businesses may adopt such systems in the future and diversify their cage culture operations. Existing models may or may not be adequate to evaluate carrying capacity in this regard. Thus it is important to consider both present systems such as monoculture and potential IMTA systems when evaluating models for development, management and regulation of European aquaculture.

TAPAS will evaluate the regulatory models (DEPOMOD, Ancylus MOM) and other models (e.g. CAPOT) and approaches using case studies in Norway, Ireland and the Mediterranean Sea. Dynamic models will also be developed to assess the differences in nutrient flow between monoculture and IMTA systems and the implications for carrying capacity and site selection, as well as the models used for management and regulation.

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3. Water body level models for marine fish culture systems

3.1. Water body level

Marine cages are normally located in areas that are considered common property resources, like an area of coastline, so generally the farmer will have little or no control over other developments and activities in the area (Beveridge et al., 2004). Thus it is important to not only consider potential impacts and interactions at the farm scale (Section 2) but also at the water body level. There is some overlap between the farm scale models and water body level models and some of the models can be used for both scales. However, generally, water body level models focus more on the hydrodynamics and are often more complex than the local level models. At the waterbody scale models can also consider the impact of multiple farms and/or activities and thus consider the cumulative impacts.

3.2. Models

Unlike most farm scale models for marine fish culture systems, water body level models are not necessarily developed and used for aquaculture. MIKE 21, MIKE 3, Delft3D, MOHID, POLCOMS and FVCOM are examples of this. These models can be used to simulate complex processes and can be used to estimate carrying capacity and environmental impact of aquaculture at a wider scale than farm level models.

3.2.1. MIKE 3

MIKE3 is a modelling suite developed by DHI (https://www.mikepoweredbydhi.com) and used for coastal engineering and environmental studies. MIKE3 is modular so users can purchase and link the modules they require and there are also different licence types available depending on user requirements. The MIKE 3 Flow Model FM (Flexible Mesh) includes a number of modules of which the following modules are relevant for aquaculture farming purposes: Hydrodynamic Module (HD), Advection and Dispersion Module (AD), Ecology and Water Quality Module (ECO Lab).

In addition to the MIKE 3 FM model and modules the spectral wave model (SW) has been included to provide a basis for estimating shear stress as part of estimating potential re-suspension of particulate waste. Both the MIKE 3 FM and the SW model utilize an unstructured flexible mesh (FM) grid. An unstructured flexible mesh (FM) grid provides an optimal degree of flexibility in the representation of complex geometries and enables smooth representations of boundaries. Small elements may be used in areas where more detail is desired (e.g. in semi-enclosed fjords) and larger elements used where less details are needed (e.g. in open waters, optimizing resolution for a given amount of computational time. The spatial discretization of the governing equations is performed using a cell-centred finite volume method. In the horizontal plane, an unstructured grid is used, while a structured mesh is used in the vertical domain (3D).

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Hydrodynamic Module

MIKE 3 HD FM solves the Reynolds-averaged Navier-Stokes equations for conservation of mass and momentum in three dimensions. The flow field is computed in response to a variety of forcing functions, when provided with the bathymetry, bed resistance, atmospheric forcing, open boundary conditions, etc. The hydrodynamic phenomena included in the equations includes tidal flows and currents; turbulent diffusion, entrainment and dispersion; baroclinic flows & wind-driven circulation; effects of the rotating earth described mainly through the Coriolis terms; response to variable bathymetry and dissipation from seabed resistance; flooding and drying of inter-tidal areas; air-sea heat exchange; hydrodynamic effects of rivers.

The unstructured flexible mesh consists of triangles and quadrahedrals of varying size in the horizontal plane. This approach allows for a variation of the horizontal resolution and element shape of the model mesh within the model area to allow for a suitably fine discretization of selected sub-areas, such as aquaculture farm areas, where each cage typically is represented by 1-to-4 grid cells (cage-size dependent).

In the vertical, a structured mesh is applied, often based on a mixed sigma-z-coordinate transformation. Above a fixed transition depth (0-10m), the water column is divided into a fixed number of layers varying in thickness with total water depth. Below the transition depth, the vertical discretization is based on a specified thickness for each layer (ranging between 1-30 m).

Water Quality Module

The ECOLab water quality (WQ) module employs an algal growth model describing growth, death, grazing and other processes which consume, produce and transform algae and nutrients. Algae grow by photosynthesis. Their growth rate is determined by temperature, availability of light and availability of nutrients (described by Droop-kinetics). The model describes the variation in time of concentrations of a range of components defined as state variables in the pelagic and benthic phases.

The user specifies the detail of the “ecosystem-structure” required. In a standard DHI-setup models consist of phytoplankton in 3 functional groups or are lumped into one group with seasonal variability representing different functional groups. The phytoplankton functional group(s) are specified in terms of their carbon, nitrogen and phosphorous content. For zooplankton a fixed C:N:P relationship is assumed, and therefore only the C pool is described explicitly. Also defined are inorganic nutrients and organic particulate matter (detritus). Compared with earlier ECOLab ecosystem models, a recent feature is the inclusion of explicitly defined pools of dissolved organic nutrients, including both labile and refractive fractions. The transport of the pelagic components is calculated on the basis of results from the hydrodynamic model, see Figure 3.1.

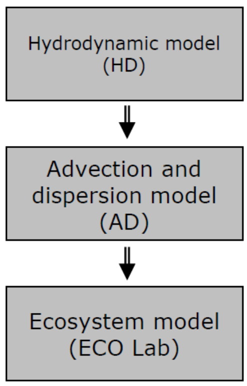

Figure 3.1 The basis for the ECO Lab model

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Ad HD: As described above the MIKE 3 FM hydrodynamic model solves the Reynolds-averaged Navier-Stokes equations for conservation of mass and momentum in three dimensions to calculate the flow of water masses, driven by meteorological and other boundary conditions, and delivers the transport and dispersion basis for the AD module.

Ad AD: An advection and dispersion (AD) model calculates the transport of pelagic components based on the flow conditions described by the HD model. This transport is a combination of advection, the direct movement of the material contained by a volume of water and dispersion, the transport due to unresolved effects which take place on a smaller scale than the model grid. The AD model also includes addition of material to the system via point sources and the transport in/out of the model domain across open boundaries.

Ad ECO Lab: The ecosystem (biogeochemical) model describes the important processes which generate, consume or transform material being part of the biogeochemical system and the interactions between the components defined as state variables for the system, see Fig. 3.2 and Fig. 3.3 These processes include the growth of different algal functional groups. The ECO Lab model can also describe sedimentation and buoyancy processes which can transport state variable components vertically in the water column independently of advection and dispersion.

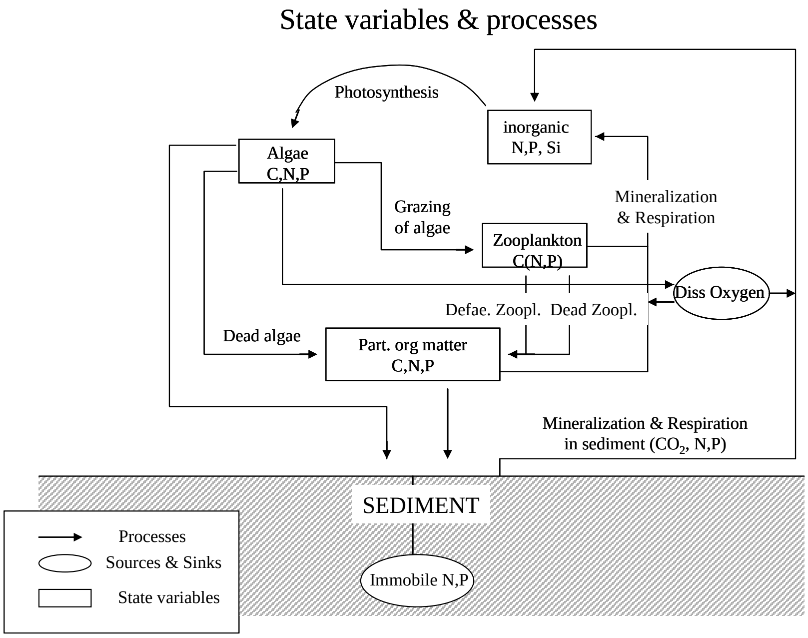

Figure 3.2 Simplified pelagic flow chart for the ECOLab module

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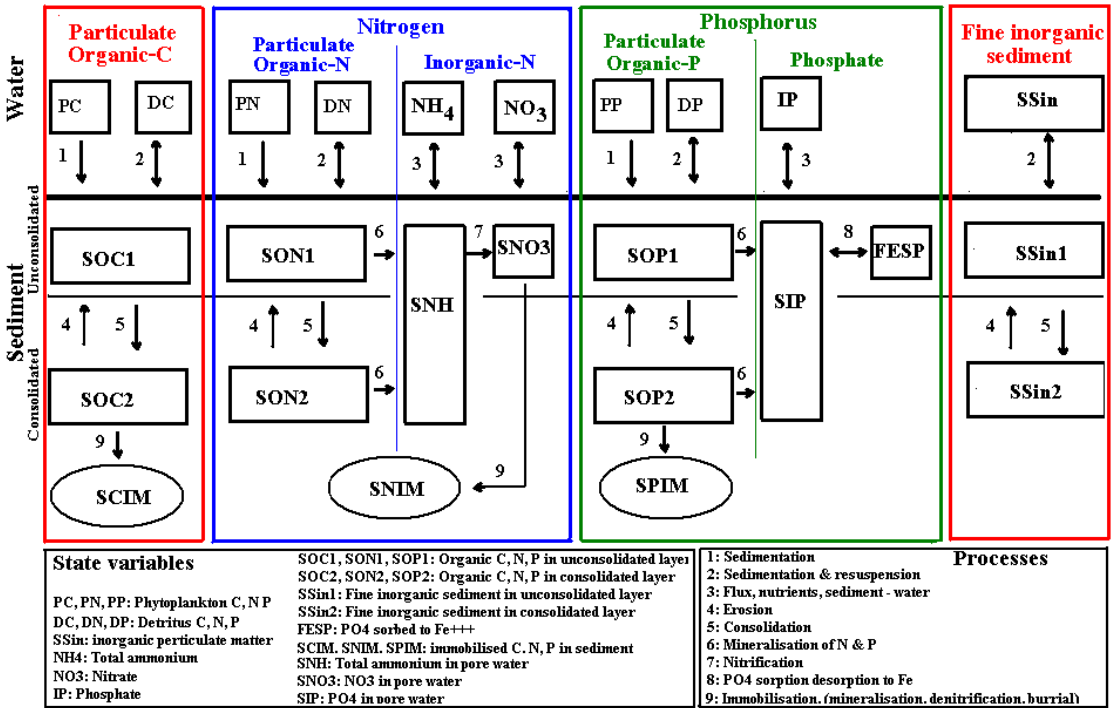

Figure 3.3 Sediment flow chart for the ECO Lab module

The ecosystem model is defined in a template. This template specifies the differential equations which describe the variation in time of the concentrations of components defined as state variables. The differential equations for these state variables included in the model are defined as the combination of one or more processes. The sediment pools of nutrients are also represented in the ECO Lab template, see Fig. 3.3.

Model calibration parameters: Also included in the model definition are a large number of constants, including, for example, specific growth and death rates, specific light absorption coefficients, coefficients for temperature dependency of different biological processes, settling rate of particles (phytoplankton, detritus, fish faeces, feed pellets etc. Such constants are calibration parameters for the ecosystem model and are initially chosen based on values found in literature and many years of experience with other model applications.

Overall, MIKE3 and the associated “ecosystem” equation solver ECOLab have been applied in more than 30 studies supporting farmers to select production sites, to predict environmental impacts of current and new farms and to estimate carrying capacity of water bodies. In Brazil, MIKE3 was used by the company contracted by the state of Rio de Janeiro to produce their Local Plan for Mariculture Development (Scott, 2013). MIKE3 has also been used to predict jellyfish outbreaks around Shetland, Scotland (Elzeir, 2005). Jellyfish can cause fish health problems and mortalities in fish farms (Baxter, 2011), models developed using MIKE3 can provide an early warning system for farmers (Elzeir, 2005).

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Table 3.1: Overview of MIKE3

Strengths	Limitations or weaknesses
+ modular design and seamless integration between modules + wide range of applications including tidal flows, density flows, other advection-dispersion problems, advanced water quality modelling, agent based modelling and sediment dynamics + menu-driven user interfaces + includes a large number of productivity tools to prepare input and interpretation as well as presentation of results + extensive documentation, user support, yearly updates and "ecosystem" templates available	- Expensive, but available to research institutions at reduced rates if used for educational purposes and non-commercial work. - Considerable collection and time requirement for acquisition of date for effective use. - Significant expertise (training course) required to use
Summary: MIKE3 is a sophisticated modelling suite that can be used for many different purposes. It is a flexible system comprised of different modules, several of which are useful for aquaculture.	

3.2.2. Delft3D

Developed by Deltares (https://www.deltares.nl/en/), Delft3D is a modelling suite containing several engines (including Delf3D-Flow, DELWAQ, Delft3D-Wave), GUIs for each engine and tools. It is used to simulate two-dimensional and three-dimensional flow, sediment transport and morphology, waves, water quality and ecology as well as interactions between the processes. It is a commercial product and Deltares offer a wide range of fee-based services as well as support and assistance through service packages and training courses.

In Brazil, the fisheries extension service of the state of Bahia, used Delft3D to assess the hydrodynamics of the Todos os Santos Bay prior to proposing areas for aquaculture development (Scott, 2013). Ferreira et al. (2014) used Delft3D-FLOW together with EcoWin (an ecological model that can be used to assess nutrient loading and aquaculture development scenarios (Ferreira, 1995)) to assess the performance of an aquaculture park. This approach was used as the FARM model was not considered appropriate for local-scale simulation due to the size of the designated area and the complexity of water circulation (Ferreira et al., 2014). Delft 3D-Flow was also used in the disease component to assess the hydrodynamic connectivity between the offshore and inshore areas used for clam culture and to generate risk maps (Ferreira et al., 2014).

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Table 3.2: Overview of Delft 3D

Strengths	Limitations or weaknesses
+ Contains different modules that can be used for many applications + Developed over many years in a commercial environment + Capable of modelling complex hydrological processes	- It is a commercial product and it is expensive, although support is provided from the company. - Considerable collection and time requirement for acquisition of date for effective use. - Significant expertise (training course) required to use
Summary: Delft 3D is a complex commercial modelling suite that has a wide range of applications.	

3.2.3. MOHID

MOHID is a water modelling system that simulates surface water bodies, developed by MARETEC (Marine and Environmental Technology Research Center) at Insituto Superior Técnico (IST), Technical University of Lisbon (www.mohid.com). First developed in the late nineties, MOHID has been adapted and refined ever since, for use by researchers and professionals across a large range of scales and physical conditions (Neves, 2013). MOHID is programmed in ANSI FORTRAN 95 using an object orientated philosophy to simulate eulerian and lagrangian processes (Perán et al., 2013). The core of the model is a fully 3D hydrodynamic model that is coupled to different modules (Neves, 2013; Perán et al., 2013).

Moreno et al. (2011) coupled MOHID to a particulate tracking model to study the effect of hydrographic condition on the behaviour of waste from a salmon cage in Mulroy Bay, Donegal, Ireland. The results were also incorporated into GIS to provide a graphical user interface, temporal visualisation and interrogation of results (Moreno et al. 2011). To illustrate mixing of the water (effluents from cages), an animated dispersion model was produced, where the particles in different cages were colour-coded and the model simulated one day (Figure 3.4; Moreno et al. 2011). This highlights the advantage of modelling at a waterbody scale as there is the potential to consider multiple farms

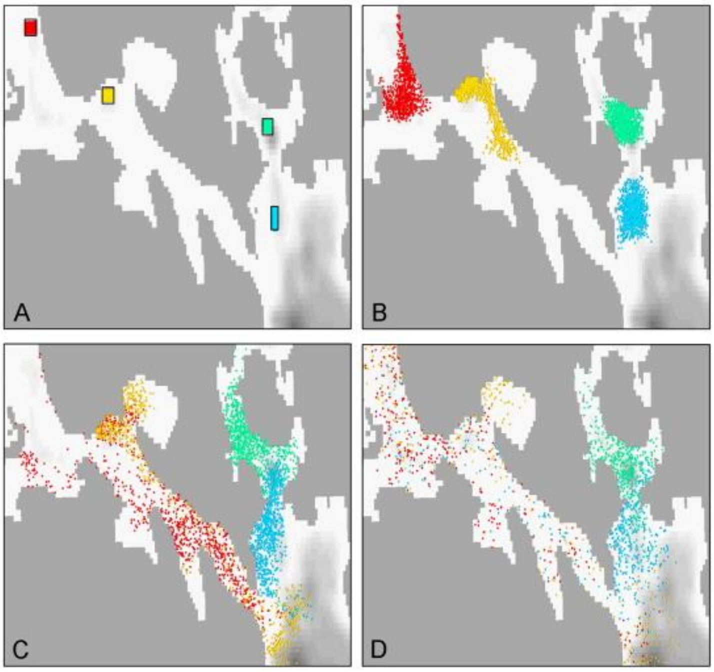

Figure 3.4: Stills from the animated dispersion model developed using MOHID coupled to a waste dispersion model. The initial position of the four cages is shown by the boxes (A) and subsequent dispersion pattern is illustrated in B, C and D (Moreno et al., 2011)

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and cumulative impacts. Such impacts may be missed, or difficult to detect, at the farm scale.

Other studies have used MOHID modules for assessment of aquaculture. Tironi et al. (2010) combined MOHID with the MOHID Langrangian Module (to simulate particulate wastes) and a GIS application into a waste dispersion tool for assessing salmon farms in the Aysen Fjord, Chilean Patagonia. Although there was insufficient data available to fully validate the model, local decision makers used the model as a management tool (Tironi et al., 2010). Perán et al., (2013) coupled the MOHID WaterQuality module (a nutrient-phytoplankton-zooplankton-detritus (NPZD) module to the hydrodynamic module to simulate nitrogen, phosphorus and oxygen cycles in the water column and bottom sediments in a study area located 6km from the coast in the southeast of the Iberian Peninsua, Spain. Both models produced by Tironi et al. (2010) and Perán et al., (2013) require further validation. In addition, as noted by Scott (2013), to improve the usability of MOHID modules as waste dispersion models for aquaculture the system should be compared with other models such as DEPOMOD.

Table 3.3: Overview of MOHID model

Strengths	Limitations or weaknesses
+ Open source software + Includes different modules that can be used for aquaculture	- Further studies needed to validate MOHID and the MOHID modules for aquaculture - Considerable collection and time requirement for acquisition of date for effective use. - Significant expertise (training course) required to use
Summary: MOHID can be used to model processes in surface water bodies. There have been several applications for aquaculture site selection and assessment of environmental impacts but it is complex to use and some expert knowledge is needed.	

3.2.4. FjordEnv

FjordEnv (www.ancylus.net) is an internet-based simplified physical/biogeochemical model with a built-in fish farm model. Although not a formal requirement of the regulatory process, FjordEnv is widely used throughout Norway by marine consultants, research institutes and in education. It can also be coupled to the regulatory MOM system (See section 2.3.2). The model has been developed and refined over the years and is now available as a web application and users can pay to access the model (a one year subscription is €590). Although FjordEnv has been developed for inshore waters along the Norwegian coast and Baltic Sea it can be applied to inshore waters in any inshore area of the ocean and large lakes if values of model parameters are available (Ancylus, n.d). The ACExR model (Section 3.3.5) that is used in Scotland is an adapted version of FjordEnv (Tett et al., 2011) However it is not suitable for open water systems where more complex modelling systems such as MIKE3 should be used.

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The model has been designed with simplicity in mind and effort has been made to reduce input data requirements (Stigebrandt, 2001). It can be used to calculate environmental impacts of aquaculture, as well as industrial wastewater. The model is described in detail in Stigebrandt (2001) and Ancylus (n.d). In surface waters the environmental change due to nutrient input is expressed as changes in Sechhi depth, and changes in oxygen consumption and minimum oxygen concentrations are used for deeper layers (Ancylus, n.d). Environmental impacts are horizontally averaged over the whole inshore water body but MOM can be used to calculate the local scale conditions at the fish farm (Stigebrandt, 2001).

Table 3.4: Overview of FjordEnv model

Strengths	**Limitations or weaknesses**
+ Simple model with relatively simple data requirements + Available as a web based application + Although developed for the Norwegian coast and the Baltic Sea, FjordEnv can be applied to other inshore waters and lakes if model parameters are available.	- Used for inshore waters only - Very simple model
Summary: FjordEnv is a water quality model that can be used at the waterbody scale for inshore waters and lakes in Scandinavia	

3.2.5. ACExR-LESV

ACExR-LESV is a physical-biological model that is used to estimate the assimilation capacity of fjordic water bodies in Scotland (Tett et al., 2011). ACExR is the physical part of the model, which uses FjordEnv equations (Stigebrandt, 2010) that have been adjusted to allow dynamic simulation of day to day changes (over the year) in temperature, salinity, thickness and exchange rates of three layers (Tett et al., 2011). The modifications improve simulation of tidal exchange, as noted by Tett et al. (2011), this is important for the west coast of Scotland which has a tidal range of several metres, compared to southern Norway where FjordEnv is normally applied which has a tidal range of less than half a metre.

The Loch Ecosystem State Vector (LESV) model is the biological component of ACExR-LESV (Portilla et al., 2009) and allows estimation of waste assimilative capacity (Tett et al., 2011). At present the model can be used for finfish farms but Tett et al. (2011) suggest the model could be improved to allow consideration of mussel farming and potential assessment of IMTA systems, taking into account nutrient recycling by filter feeders. As noted by Tett et al. (2011) reliable use of the model is dependent not only on the model algorithms and parameters but also the boundary conditions.

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Table 3.5: Overview of ACExR-LESV

Strengths	Limitations or weaknesses
+ More suitable for use in Scotland than FjordEnv + Couples a physical model with a biological model	- Only used for finfish, but in the future could be updated to consider shellfish
Summary: ACExR-LESV is a physical-biological model that can be used in Scotland to estimate assimilation capacity of inshore water bodies in Scotland. The ACExR model is based on FjordEnv but includes adaptations for water bodies in Scotland.	

3.2.6. EcoWin2000 (E2K)

Ecowin2000 (www.longline.co.uk) is an ecological model developed using an object-oriented approach that can be used to assess nutrient loading and aquaculture development scenarios (Ferreira, 1995). EcoWin2000 uses a range of equations depending on the application requirements and includes hydrodynamics, biogeochemistry and can incorporate population dynamics for target species (Ferreira et al., 2008a). EcoWin2000 has two main components: the central core, which is the module responsible for communication between objects, user interface, production of model results and routine maintenance tasks, and the ecological objects (Ferreira et al., 2012b). Although EcoWin2000 is coarser than fine scale hydrodynamic models, it runs quickly and does not need as much data (Ferreira et al., 2008b).

Table 3.6: Overview of the EcoWin model

Strengths	Limitations or weaknesses
+ Model has been optimised to run quickly + Dynamic model that can be used for short term and multi-year simulations	- Not appropriate for farm scale models - Coarser resolution than more detailed hydrodynamic models
Summary: EcoWin2000 is a framework that integrates multiple modules; hydrodynamics, biogeochemistry etc to assess nutrient loading and aquaculture development scenarios.	

3.2.7. Aquaculture Integrated Model (AIM)

The Aquaculture Integrated Model (AIM), developed at Hellenic Centre for Marine Research (HCMR), is based on a complex generic biogeochemical model coupled to a 3D hydrodynamic model and has been applied to study areas in the Mediterranean Sea (Tsagaraki et al., 2011; Petihakis et al., 2012). The biogeochemical model is based on the European Regional Seas Ecosystem Model (ERSEM) (Baretta et al., 1995) that follows a "functional" group approach where the ecosystem is described in

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terms of functional roles (producers, consumers, decomposers). The pelagic plankton food web is adequately described with four phytoplankton groups (diatoms, nanoplankton, picoplankton, dinoflagellates), three zooplankton groups (heterotrophic nanoflagellates, microzooplankton, mesozooplankton) and bacteria. This complex food web is then used to consider the transfer of carbon and nutrients between organisms and the environment (Figure 3.5). ERSEM is also equipped with a comprehensive benthic model (Ebenhoh et al., 1995) that can be used to examine the effect from fish farms nutrient fluxes on the benthic ecosystem. However, this is more site specific, requiring additional data, effort and computational load and is thus not currently implemented. The three-dimensional hydrodynamic model is based on the Princeton Ocean Model (POM, Blumberg and Mellor, 1983), a widely spread community model (www.ccpo.odu.edu/POMWEB/). POM is a primitive equation, free surface and sigma-coordinate circulation model (Petihakis et al., 2012). A series of nested models is used to consistently downscale the hydrodynamics and biogeochemistry from the coarser resolution (~few kilometres) model of the wider area to the high resolution model (~few tens of meters) of the fish farm area of interest (Figure 3.6). The amount of nutrients entering the environment from the fish cages is calculated using a mass balance approach.

The model produces maps of Chl-a, dissolved inorganic nutrients (phosphate, nitrate, ammonium, silicate), dissolved oxygen, plankton biomass and production. It can be used to examine the fate of the aquaculture wastes under different scenarios (fish production, fish farm locations etc, see Figure 3.7) and assess their possible impacts on the surrounding ecosystem in terms of good environmental status.

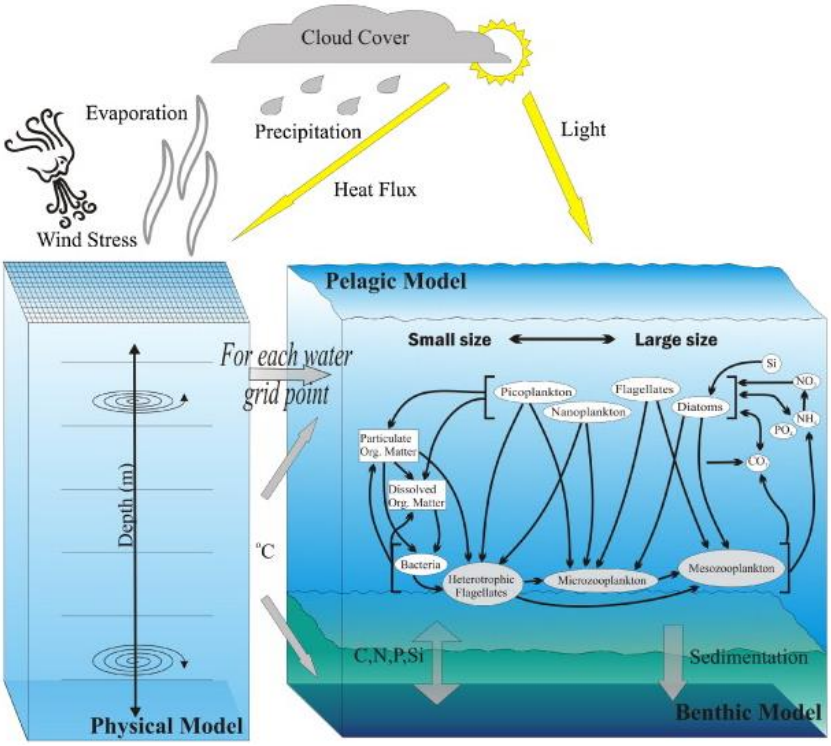

Figure 3.5: Schematic diagram of the AIM biogeochemical model (Tsagaraki et al., 2011).

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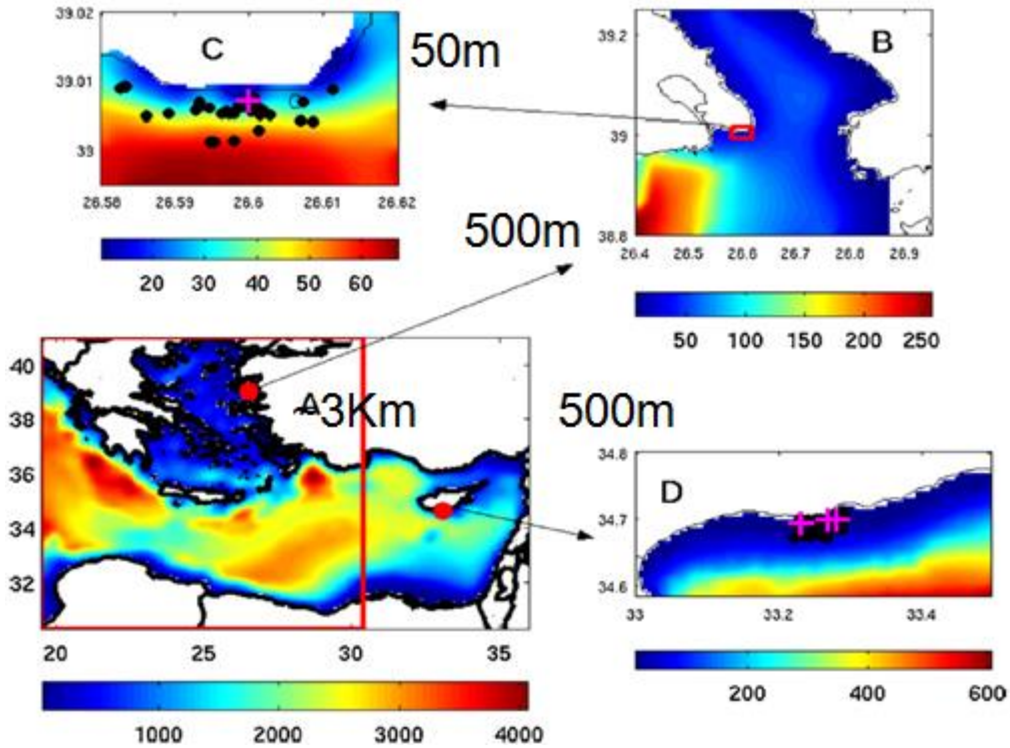

Figure 3.6: Domain and bathymetry of AIM nested models downscaled from coarse (~3Km) to fine (~50m) resolution at farm scale (Tsagaraki et al., 2011)

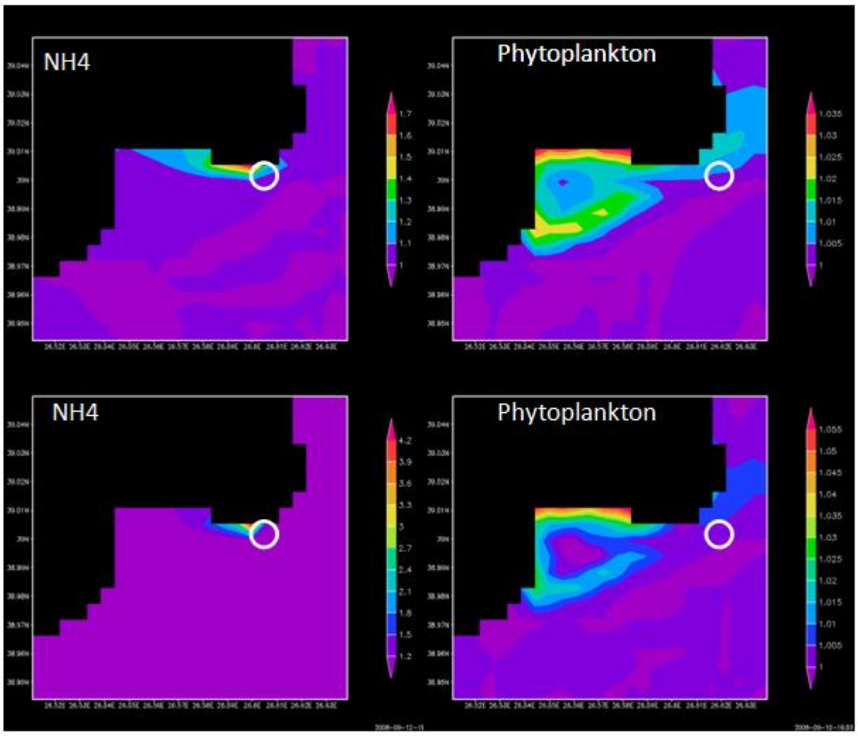

Figure 3.7: Simulated ammonium (left) and phytoplankton biomass (right) ratio of scenarioC/scenarioB (top) and scenarioB/scenarioA (bottom), where scenarioA=no fish farms (pre-establishment), scenarioB=present conditions and scenarioC= fish production x 2 (Tsagaraki et al., 2011).

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Table 3.7: Overview of AIM model

Strengths	Limitations or weaknesses
+ Based on established techniques and approaches + Comprehensive biogeochemical model (potentially including benthos) + Can consider far field impacts	- Computational cost may be high, depending on resolution - Not widely used by regulators
Summary: AIM is based on a complex generic biogeochemical model coupled to a 3D hydrodynamic model and can be used to assess impact of aquaculture on the ecosystem.	

3.2.8. FVCOM-ERSEM

Plymouth Marine Laboratory has developed a coupled modelling system FVCOM-ERSEM to resolve the evolution of coastal and nearshore environmental conditions in response to natural variability, climate change or anthropogenic activities. The system integrates the hydrodynamic model FVCOM (Finite Volume Coastal Ocean Model) with the lower trophic level ecosystem model ERSEM (Earth and Regional Seas Ecosystem Model). The model system is written in FORTRAN 95, it is highly modular and customisable but requires expert knowledge and access to high performance computing to use it.

FVCOM is a finite-volume coastal ocean model (Chen *et al.*, 2003; 2006) which makes use of an unstructured (usually triangular) mesh. It solves the hydrodynamic momentum and continuity equations plus conservation equations for various tracers by a time-stepping procedure, giving a time-evolution of water level, 3D currents, temperature, salinity and water quality. The unstructured grid nature of FVCOM allows for different model resolution to be used across the domain enabling the description of hydrodynamic processes at scales that are applicable to farm management issues simultaneously to describing the evolution of the marine environment at the water body level. FVCOM has been used for a wide range of applications, from marine renewable impacts (Cazenave et al. 2016) to aquaculture (Foreman et al., 2015).

FVCOM can additionally be used to estimate residence times (i.e. of potential pollutants used in some aquaculture activities), dispersion patterns (e.g. parasite dispersion), behaviour of aquaculture waste or connectivity characteristics of sub-regions or individual farms by applying a lagrangian tracking model like PyLag also developed at Plymouth Marine Laboratory.

ERSEM (Baretta et al., 1995; Blackford et al., 2004; Butenschön et al., 2016) is a biomass and functional group -based biogeochemical model describing the nutrient and carbon cycle within the low trophic levels of the marine ecosystem (Figure 3.x) . Model state variables include living organisms, dissolved nutrients, organic detritus, oxygen and CO_2. Pelagic living organisms are subdivided in three functional groups describing the planktonic trophic chain: primary producers (phytoplankton), consumers (zooplankton) and decomposers (bacteria). Primary producers and

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consumers are subdivided into 4 and 3 size-based functional types, respectively. The phytoplankton community is composed of picophytoplankton, nanoflagellates, dinoflagellates and diatoms, while the zooplankton community is composed of mesozooplankton, microzooplankton and heterotrophic nanoflagellates. Decomposers are modeled by one type of heterotrophic bacteria. Functional types belonging to the same group share common process descriptions but different parameterizations.

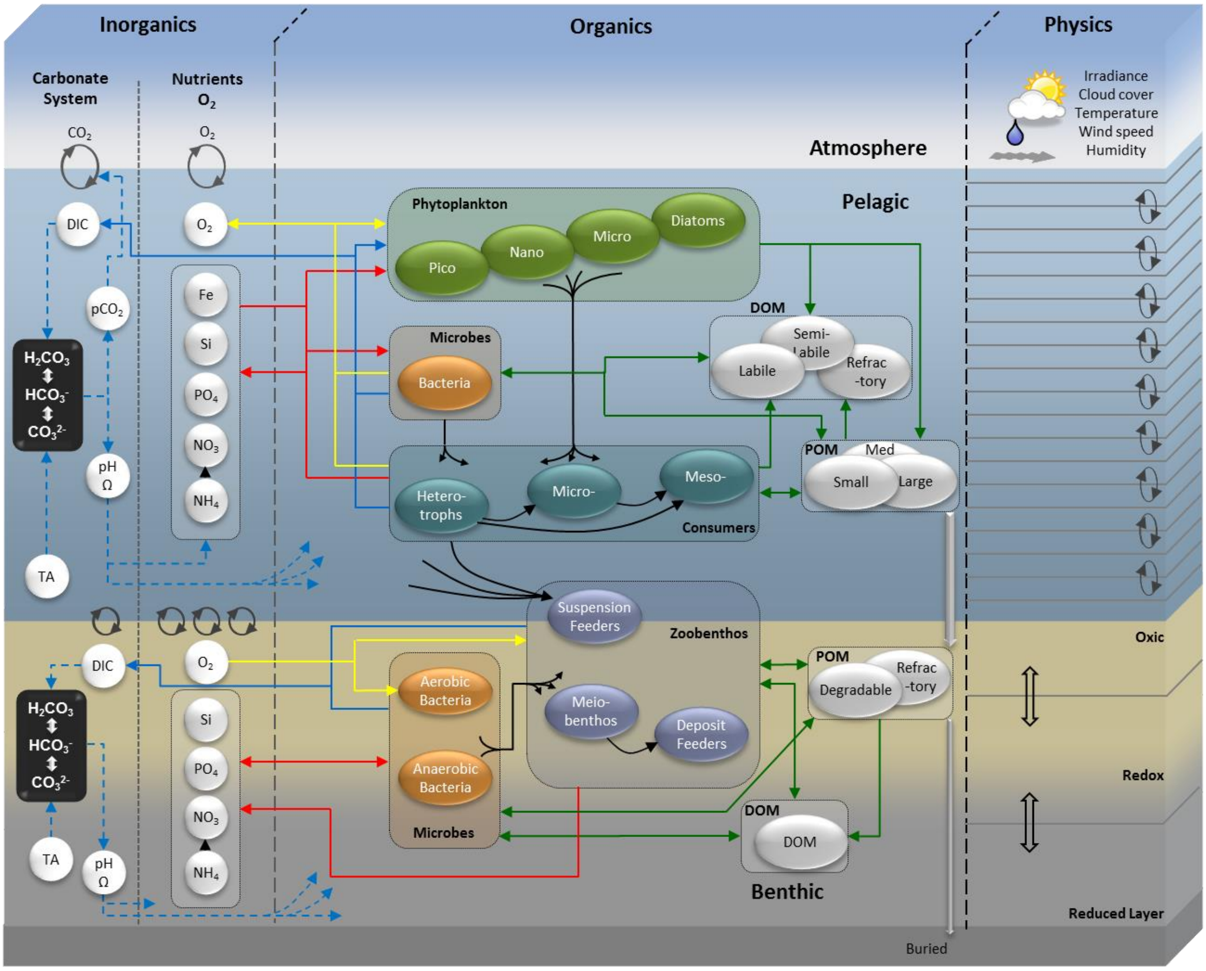

Figure 3.8: Schematic of the ERSEM model in its default configuration coupled to a generic hydrodynamic model

A key feature of ERSEM is the decoupling between carbon and nutrient dynamics allowing the simulation of variable stoichiometry within the modeled organisms. Chlorophyll is also treated as an independent state variable following the formulation by Geider et al. (1997). Consequently each plankton functional type is modeled with up to five state variables describing the cellular content of carbon, nitrogen, phosphorus, silicon, and chlorophyll-a. Dissolved organic matter (DOM) is produced by different processes involving phytoplankton, bacteria and zooplankton while its consumption is exclusively regulated by bacteria uptake. DOM is subdivided into labile, semi-labile and semi-refractory components (Polimene et al., 2006), in order to provide a representation of the range of organic compounds present in the marine DOM and their different levels of degradability.

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Particulate organic matter (POM) is produced by phytoplankton and zooplankton and it is divided into three size-based categories corresponding to different sedimentation rates.

All the ERSEM equations are detailed in Butenschön et al. (2016) and we refer the reader to that paper for a comprehensive description of the mathematical formulations used in the model.

The use of FVCOM-ERSEM can help evaluate how aquaculture activities can influence the marine environment and how the marine environment can support aquaculture activities. Estimates of carrying capacity (see section 4) can be achieved when aquaculture models are included within the model system (e.g. ShellSIM). ERSEM can also be used to estimate the potential processing of aquaculture waste (e.g. processing of POC by pelagic and benthic lower trophic communities) and can provide information on site suitability for exploring aquaculture development options (i.e. interannual variability of primary production).

Table 3.8: Overview of FVCOM-ERSEM model

Strengths	**Limitations or weaknesses**
+ Based on established techniques and approaches + comprehensive carbonate system enabling climate impacts on shellfish +Fully modular and therefore customisable to studies requiring different ecosystem structure + ERSEM has been coupled to a variety of hydrodynamic models, from fine scale models (i.e. FVCOM) to regional (POLCOMS, ROMS) and global models (i.e NEMO) + extensive literature supporting a wide range of applications	- requires expert knowledge - needs access to high performance computing infrastructure- small supporting evidence of its applicability in aquaculture studies beyond academic research - complex model system than can be difficult to modify without expert knowledge
Summary: FVCOM-ERSEM is a coupled hydrodynamic ecosystem model capable of simulating the evolution of coastal and nearshore biogeochemistry at the relevant scales for aquaculture activities. The high computational requirements means the modelling system has been primarily used for academic research.	

3.2.9. SWAN and ROMS

The Simulating Waves Nearshore Model (SWAN - http://www.swan.tudelft.nl/) is a third generation wave model that computes random, short-crested wind-generated waved in coastal regions (Booij et al., 1999). ROMS (the Regional Ocean Modelling System - https://www.myroms.org/) is an open-source, primitive equation, free-surface, hydrostatic, fully 3D community ocean model (Shchepetkin and McWilliams, 2005). Both models were used as part of an Environmental Impact Statement for proposed salmon farms in Ireland. The modelling scenarios simulate the wave climate in the area of

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the proposed farms and also simulate the fate of tracers released at those sites. The models are well-established, validated models and were run operationally by the Marine Institute, Ireland.

The wave model was developed using an open source SWAN (Simulating Waves Nearshore) code. Modelled wave data was used to characterize the wave climate and extreme wave events at the proposed sites. Hydrodynamic modelling was used to simulate the dispersion of tracers (e.g. ammonia, sea lice) and solids (salmon feed and faeces) released from the proposed farms. Dissolved tracer dispersion studies were used to derive flushing times and ammonia dispersion, sea lice dispersion was carried out using the particle tracking functionality and faeces and feed transport was simulated using a sediment transport model. This highlights an approach using multiple models to assess site suitability and environmental impact.

3.3. Strengths and Weaknesses

Fully 3D hydrodynamic models have an advantage over simpler Lagrangian models like DEPOMOD as they are able to simulate both dissolved and particulate discharges and represent heterogeneous hydrodynamic fields (Perán et al., 2013). However, they need more computational power and often require expert knowledge to operate; as with all models there is a trade-off between model complexity and required effort and data. Some models are more complex than others, likewise the scale and detail associated with the model will vary. One of the key strengths is the ability to model large areas. Consequently, they can also be used to consider cumulative impacts of multiple farms, something that may be missed with local level models.

3.4. Summary and recommendations for models

It is important to evaluate the use of water body scale models for nutrient waste dispersion and wider environmental impacts. There are many models available that could be used for management and regulation. TAPAS will evaluate several models and applications during the project. MIKE3 is a commercial modelling suite and will be used to quantify environmental impacts of aquaculture in the Baltic Sea. The AIM model will be used to examine the effect of aquaculture on ecology of the water column and the lower trophic levels (phytoplankton and bacteria). The models will consider different scenarios and evaluated in terms of suitability as a regulatory tool. Water body level models can also be used with other 'types' of models, for example the shellfish model ShellSim (Section 4.3.1), and this approach will also be employed.

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4. Carrying capacity models for shellfish culture

4.1. Shellfish culture

Bivalve molluscs (mussels, oysters, clams) dominate shellfish production in Europe with Spain, France, Italy and the Netherlands among the highest producers (FAO Fishstat J, 2016). The most popular species include Mediterranean mussel (Mytilus galloprovinciallis), Blue mussel (*Mytilus edulis*), Pacific cupped oyster (*Crassostrea gigas*), Grooved carpet shell (*Ruditapes decussatus*) and European flat oyster (*Ostrea edulis*). Different culture techniques may be used for the same species at different stages of the growth cycle (Ferreira et al., 2011). Unlike fed finfish aquaculture systems, bivalve molluscs depend on the environment for food. Thus, the capacity of the environment to support culture, and the selection of suitable sites, is of vital importance. However, the interaction between bivalves and the environment/ecosystem is complex as bivalves are both consumers (of phytoplankton) and producers (recycling nutrients and detritus) (Gibbs, 2007).

4.2. Models

Models are an important tool for predicting shellfish growth and production carrying capacity as they can simulate the complex dynamics involved in marine systems and the subsequent impact on food availability, something that can be difficult to capture using field measurements alone (Grant and Filgueira, 2011). Environmental changes and population dynamics must be linked to feeding processes within the models (Cranford et al., 2011) to obtain the necessary holistic understanding of the system to simulate production and predict growth.

Many models have been developed to assess carrying capacity related to shellfish aquaculture (Byron and Costa-Pierce, 2013). Some of the more popular shellfish aquaculture production models that have been compiled and made available for use (subject to licences/fees) are ShellSIM and FARM. As shellfish production is dependent on the natural ecosystem for food, food web models like Ecopath can be used to assess ecological carrying capacity. Other models have been developed for specific areas/species based a variety of approaches, including dynamic energy budget (DEB) theory and scope for growth (SfG).

4.2.1. ShellSIM

Filter-feeding bivalve shellfish are highly responsive to their variable environments. Dynamic simulations are therefore required to account for the associated complexity of animal-environment interrelations. There has been a long-standing need to simulate relevant functional dependencies, towards a common model structure which may be calibrated for different species and circumstances. The solution pioneered by PML has been ShellSIM (http://www.shellsim.com), a dynamic model structure whereby a minimal set of environmental drivers affect feeding, metabolism and growth, including dependencies between those component processes of growth, drawing upon physiological principles of energy balance (Figure 4.1).

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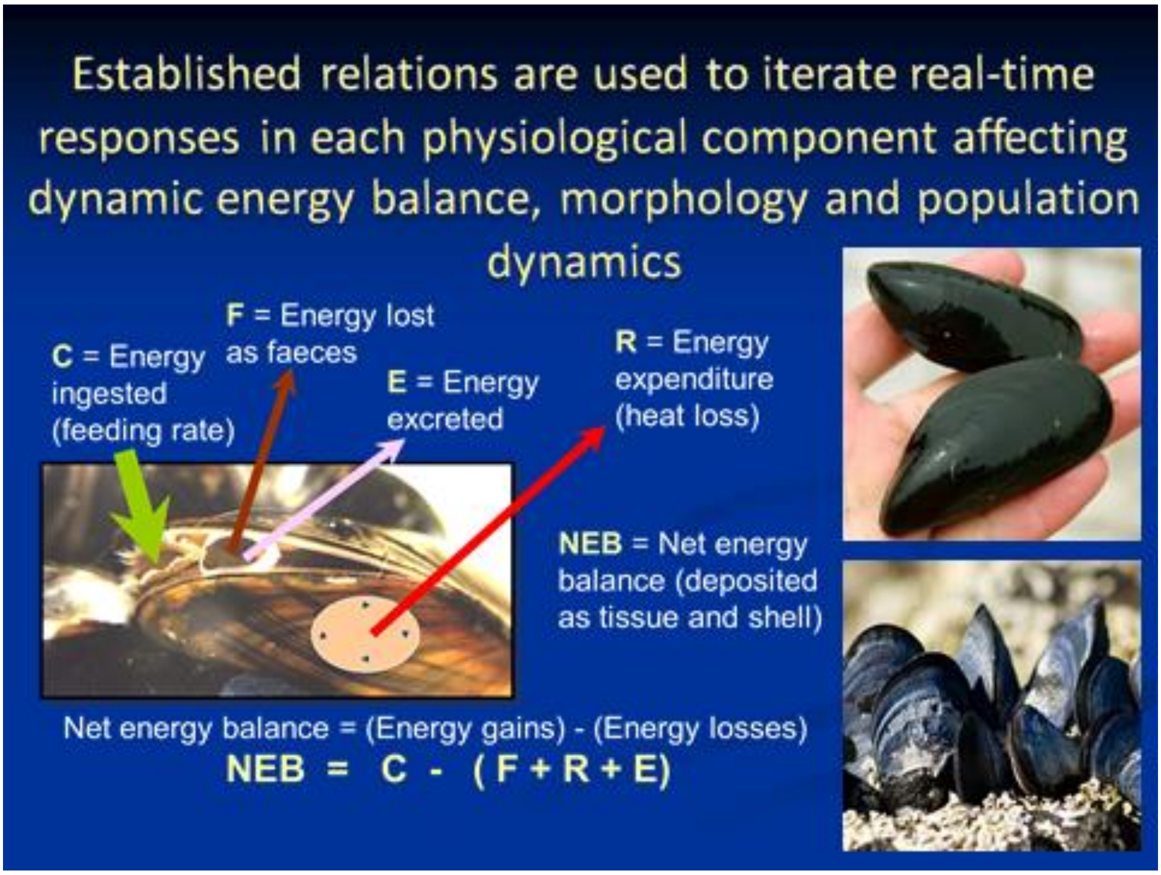

Figure 4.1: Physiological components of net energy balance predicted by ShellSIM

ShellSIM has been used in a variety of applications worldwide, simulating production capacity and effects in the management of aquaculture at farm (Bacher et al. 2003, Ferreira et al. 2007, 2009, Newell, 2012 a, b, 2013, http://www.marcon.ie/website/html/margisdemo.htm, http://www.shellgis.com) and system scales (Duarte et al. 2003, Hawkins and Duarte 2003, Ferreira et al. 2008, Sequeria et al. 2008, Nobre et al. 2010, Nunes et al. 2011).

The environmental drivers used by ShellSIM are summarized together with simulated responses in Figure 4.2. Notable novel elements of ShellSIM include resolving rapid regulatory adjustments in the relative processing of living chlorophyll-rich phytoplankton organics, non-phytoplankton organics and remaining inorganic matter during both differential retention on the gill and selective pre-ingestive rejection within pseudofaeces. This is important, for shellfish may obtain significant energy from both living chlorophyll-rich phytoplankton organics and the remaining organics such as may include detritus, bacteria, protozoans and/or colloids, when the relative abundances of different dietary components varies greatly between sites (Hawkins et al 2013).

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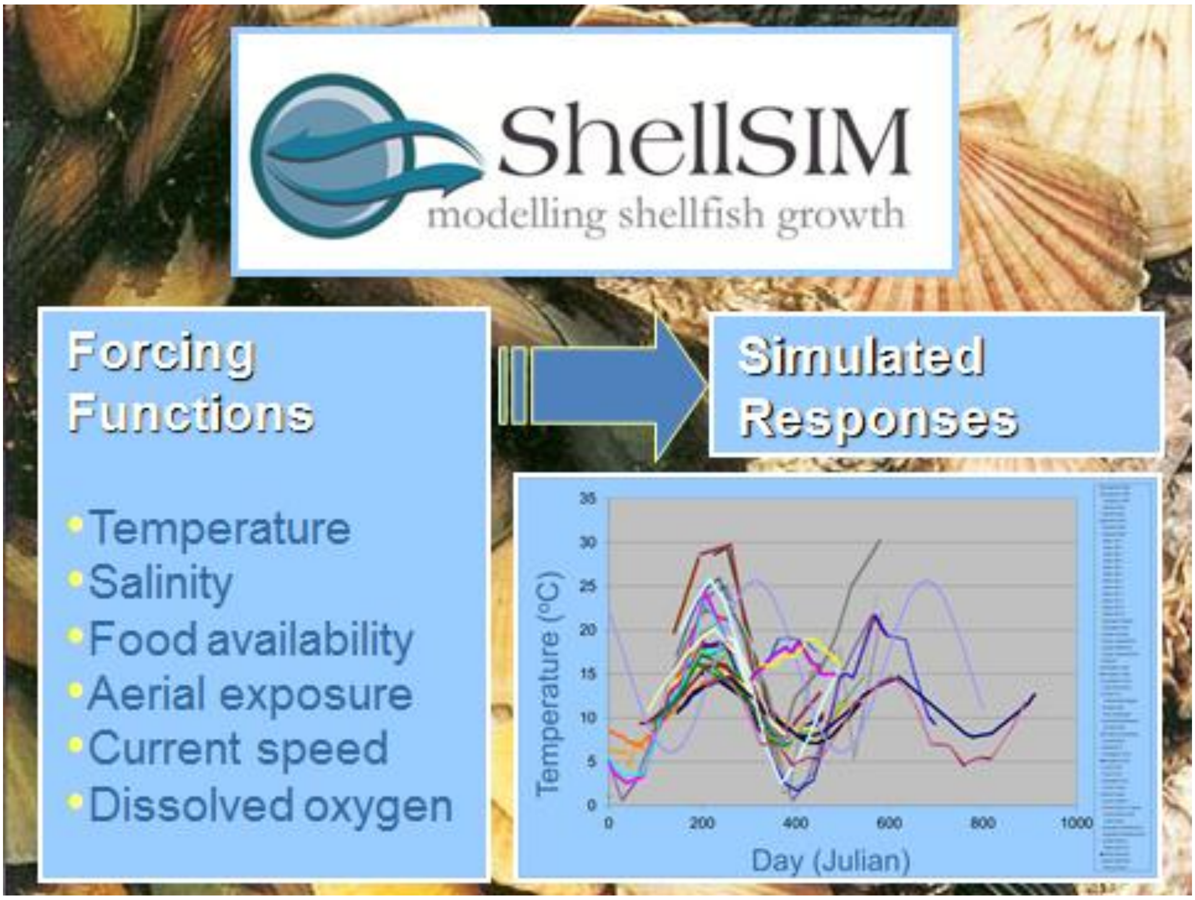

Figure 4.2: Forcing functions used by ShellSIM.

Largely by virtue of having resolved the relative processing of living chlorophyll-rich phytoplankton organics from remaining organics, then applying a single standard set of parameters optimized per species, ShellSIM has proven able to simulate growth to < 20% error in each of *Mytilus edulis, Crassostrea gigas* and *C. virginica* across wide ranges of environment and culture practice throughout Europe and Asia (Hawkins et al., 2013). Compared with previous models, this has been an important advance, saving time and resources during application in new projects. Simpler models have neither been able to predict successfully across contrasting environments, nor able to simulate responsive adjustments in feeding and metabolism, thus providing little insight into the dynamic manner whereby suspension-feeding shellfish interact with ecosystem processes, including environmental effects such as the volume of water cleared of particles, biodeposition, oxygen uptake and nitrogen losses.

One key characteristic of ShelSIM is the ability within a single tool to analyse consequences of culture practise; the user can define the spatial distribution or farm layout, the relative composition of up to 14 commonly-cultured shellfish species, activities such as seeding, mortality and harvesting, and whether they are located on the bottom, rope, pole or trestle. ShellSIM has recently been coupled online to a coupled hydrodynamic-ecosystem model FVCOM-ERSEM (see section 3.3.8) allowing for the first time to simulate the two-way interactions between the marine environment and aquaculture activities.

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Table 4.1: Overview of the ShellSIM model

Strengths	Limitations or weaknesses
+ dynamic model that can be used for short and long term simulations + dynamically linked to environmental conditions allowing two-way feedback with biogeochemical models +Large and representative number of commercial species considered + Calibrated for a wide number of species and environmental conditions + Exists as a user-friendly configurable model and as a module for incorporation into regional ecosystem models + Includes options for defining culture practise + has been used in both research and commercial applications + has been integrated into a commercial GIS for aquaculture management applications	- Complex model that requires some expert knowledge for changing the default model structure - use within a coupled hydrodynamic-ecosystem model requires access to high performance computing facility - addition of new species requires substantial effort for calibration
Summary: ShellSIM is a highly customisable numerical model adapted for both single farm (stand-alone software) and regional applications (integrated within GIS or hydrodynamic-ecosystem numerical models) that can resolve culture practices, population dynamics and carrying capacity and environmental impacts.	

4.2.2. FARM

Farm Aquaculture Resource Management (FARM) (www.longline.co.uk) is a farm scale model that can be used to determine production carrying capacity and potential environmental impacts. Originally developed for bivalve shellfish culture (Ferreira et al., 2007), FARM has now been adapted for other systems and can also be used for integrated-multi trophic aquaculture (Ferreira et al., 2014; Ferreira et al. 2015). Thus it is a flexible tool, however the individual users cannot change the parameters so it is the developers that must adapt the model for a new species as the model is hard coded.

FARM combines physical and biogeochemistry models, shellfish growth models and screening models for determining production and assessing eutrophication (Figure 4.3) (Ferreira et al., 2007). As noted by Ferreira et al., (2007) many of the components have been used previously for carrying capacity studies and validated for systems in Europe and China. The key strength of FARM is the integration of the multiple model components within one framework. FARM was designed as a simplified screening model so it only requires a simple dataset of easily available parameters (Ferreira et al., 2007). Although this is an advantage, there may be reduced flexibility when

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modelling more complex systems. Nevertheless it is a useful model for site selection and carrying capacity. It is particularly useful for stakeholders as it has a simple user interface and does not require complex knowledge or model experience to run.

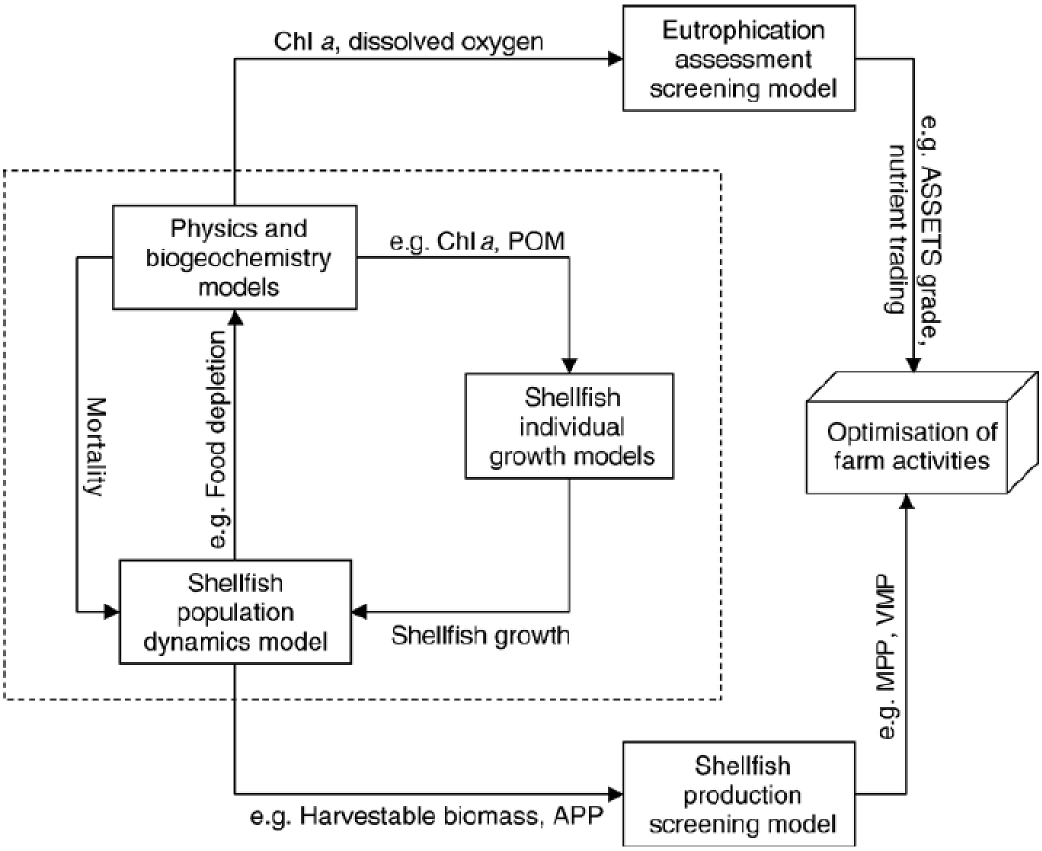

Figure 4.3: Conceptual diagram of the FARM model (Ferreira et al., 2007)

Table 4.2: Overview of the FARM model

Strengths	Limitations
+ User friendly + Requires a simple dataset + Based on established techniques + Parameterised for a number of species (fish, bivalves, shrimp and algae) + Also includes economic analysis	- User cannot change/adapt the model framework
Summary: The FARM model integrates several model components within one framework to simulate growth of shellfish	

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4.2.3. Ecopath

Ecopath (www.ecopath.org) is a static, mass-balance, ecosystem-based modelling software that has been widely used to construct food-web models of marine systems (Christensen and Pauly, 1992; Christensen et al., 2000; Pauly et al., 2000). Shellfish production is dependent on the natural ecosystem for food, and thus aquaculture will influence the food web. Although models like Shellsim and FARM are useful for determining production and environmental impact of shellfish culture, they do not consider the wider ecosystem and food web where there are other user groups and species dependent on the stability and sustainability of the entire system (Byron et al., 2011b). Ecopath has been used in several studies to calculate the ecological carrying capacity of bivalve culture (Jiang and Gibbs, 2005; Byron et al., 2011a; Byron et al., 2011b; Kluger, 2016). Ecopath, along with Ecosim and Ecospace are components of the ecological modelling package Ecopath with Ecosim. The software is free to download and use, in addition, the Ecopath Research and Development Consortium offer paid for support and there are many training courses available, all of which make Ecopath a popular tool for ecosystem and food web modelling.

Jiang and Gibbs (2005) used Ecopath to model the present state of the environment in a bay in New Zealand and then increased mussel biomass and the proportional mussel harvest (to represent development of mussel aquaculture) until suspended culture replaced the ecological role of zooplankton (the predefined significant change that represented ecological carrying capacity). Byron et al., (2011a) followed a similar approach to estimate the ecological carrying capacity of oyster culture in Narragansett Bay, Rhode Island, USA. The models can be used to develop aquaculture sustainably by calculating the maximum level of production that would not lead to significant changes (Byron et al., 2011a). However, it is important to note that Ecopath is a static model rather than dynamic. Furthermore, the models did not take into account potential disease outbreaks that could occur with an increase in bivalve monoculture or climatological variability which may also lead to variability in nutrient inputs into the system (Jiang and Gibbs, 2005). So although it considers the food-web and ecological interactions there are other factors that are difficult to include within the model. Nevertheless, Ecopath can be used with other models for a more holistic overview of a system, for example Byron et al. (2015) integrated the Ecopath model with an economic model and tested three scenarios: bivalve culture at its current state, bivalve culture at 5% of the surface area of the water body and bivalve culture at ecological carrying capacity. Thus aspects of both ecological and social carrying capacity were evaluated.

Ecopath is one of several ecosystem and food web models, however Byron et al. (2011a) suggested that compared to the other models, Ecopath represents a good balance between simplicity and complexity, and noted it provides a flexible, but structured framework for ecosystem modelling. As with any model, data availability and quality will affect model output. This is a particular issue for Ecopath as there are many unknowns and complete datasets can be difficult to obtain, especially for more complex aquatic systems (Jiang and Gibbs, 2005). Users must consider their data and acknowledge such limitations when reporting outcomes. Furthermore, Byron et al. (2011a) noted that many of the issues associated with Ecopath are due to user error and uncritical use of the

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default settings. Although described here as a tool for shellfish carrying capacity, it has also been used for other aquaculture systems, for example, Bayle-Sempere et al. (2013) characterised the trophic structure and interactions between ecological groups around a Mediterranean fish farm.

Table 4.3: Overview of the Ecopath model

Strengths	Limitations or weaknesses
+ Free to download and use **+** Considers the interaction with the wider ecosystem and other species + Structured and flexible framework + Vast amount of information available online	**-** Can be difficult to get sufficient data, particularly in complex ecosystems - Static model that does not show spatial or temporal variability
Summary: Ecopath is a food-web modelling package that can be used to assess ecological carrying capacity.	

4.2.4. Dynamic Energy Budget and Scope for Growth Models

Energy budget models are based on the modeling of ecophysiological processes and energetics of organisms in response to environmental variations. There are various types of energetic models, generally classified as “net production” or “scope for growth” models and “assimilation” or dynamic energy budget (DEB) models. In the last decade, DEB models have increasingly been developed, for various species, according to the theory developed by Kooijman (2010). The DEB theory has been successfully applied to the modeling of growth and reproduction of the various shellfish cultivated worldwide. Net production models based on the Scope for Growth (SFG) concept (Bayne 1976) use empirical relationships describing feeding processes and resource allocation, through the use of allometric relationships. Classical SFG energy allocation, which assumes that the net production (assimilation-respiration) is immediately available for growth and reproduction, considers a reserve-gonad compartment acting as a buffer. The structures of both model is described Figure 4.4.

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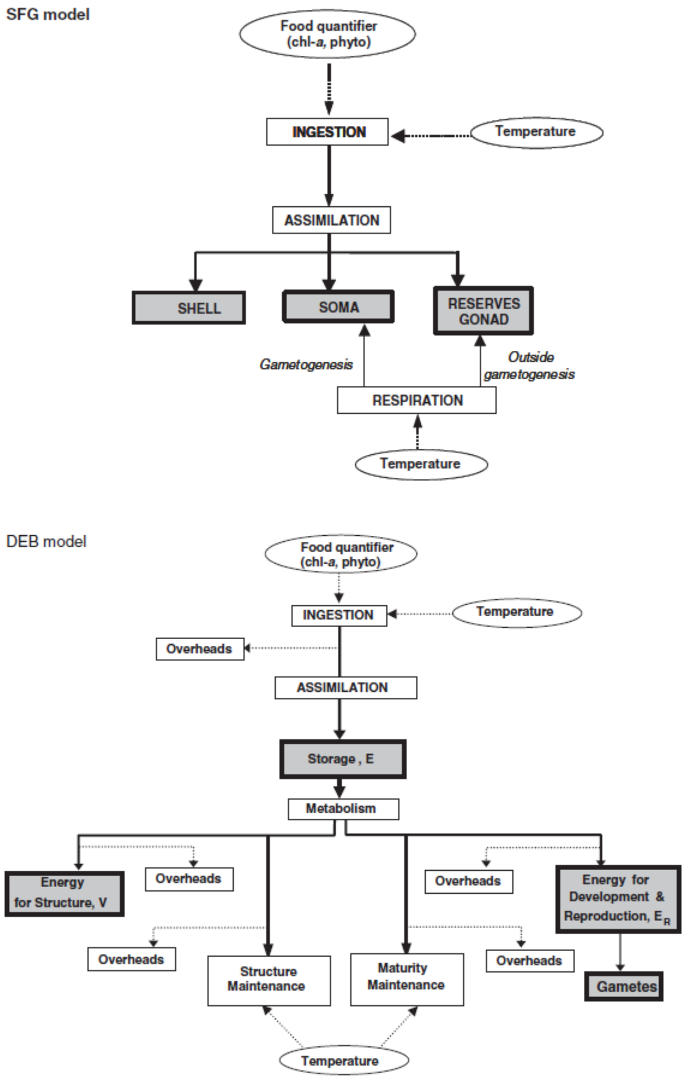

Figure 4.4:. Comparison of the structures of Scope for Growth (SFG) and Dynamic Energy Budget (DEB) models. Forcing variables are shown with ellipsis while state variables are in the gray boxes (from Barillé et al. 2011).

The main advantage of these models is to analyse each physiological responses involved in feeding and reproduction and to identify which step may be responsible for poor growth and reproduction performances. They are also useful to analyse the impact of environmental variable (eg. Food quality, turbidity) on bivalve's energy budget (Barillé et al. 2003), but they only bring information about the production carrying capacity. Although DEB and SFG models are limited to individual simulations, they can be up-scaled to population level (e.g. using Monte Carlo simulations). They often represent one component, more or less simplified, of more complex model such as ecosystems models coupling biology and physics, or farm-scale model like FARM. For example, a shellfish growth model based on DEB model has been used for rope mussel (*Mytilus edulis*) culture in Bantry Bay, Ireland (Dabrowski et al., 2013) and parameterized also for *Crassostrea gigas* in the Tagus estuary, Portugal. The model has been further developed to include physiological interactions with the ecosystem and coupled to a biogeochemical nutrient-phytoplankton-zooplankton-detritus (NPZD) model. The model is embedded within the ROMS modelling system (see section 3.3.8).

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Phytoplankton and detritus uptakes, oxygen utilization, CO_2 production, NH_4 excretion, egestion of faeces, and assimilation of food are modelled. A novel approach was derived that accounts for the allocation of C and N in mussel flesh and shell organic fraction. The DEB-NPZD model has been subsequently coupled to a high resolution three dimensional numerical coastal ocean model of the south-west coast of Ireland, where approximately 80% of national rope mussel is produced annually.

On interest of these two types of models is that they can be coupled to earth observation (EO) data to investigate temporal and spatial issues (Thomas et al., 2015). This connection is important as the EO models can provide inputs on food availability, turbidity, temperature at large scale, and particularly for off-shore projects, thus providing information for site selection and management of bivalve culture.

Table 4.4: Overview of Dynamic Energy Budget and Scope for Growth models for shellfish

Strengths	**Limitations or weaknesses**
+ Analytical tools for growth and reproduction of individuals **+** Coupling with Earth Observation data can provide synoptic views – spatial outputs that can be imported in GIS	**-** limited to individual simulations but often integrated into larger models - at this time it is mainly used as an academic tool - Requires many parameters that are difficult to estimate (although for shellfish many of these parameters are available)
Summary: The models can be used to simulate shellfish growth and used as part of a modelling framework to investigate nutrient dynamics in a waterbody.	

4.2.5. UISCE modelling system

A desktop modelling system, which incorporated *inter-alia* shellfish carrying capacity, water quality models, hydrodynamic models and flow dynamics through structures, was developed in 2008 and is currently used by Bord Iascagh Mhara (BIM), the Irish State agency responsible for developing the Irish seafood industry, for aquaculture management in Ireland. Three different types of bays and aquaculture systems were piloted; Killary Harbour for rope mussels, Wexford Harbour for bottom mussels and Dungarvan Harbour for trestle culture of Pacific oysters. The system allows a suite of management scenarios on stocking density, site layout, structure orientation, bay and farm scale carrying capacity and water quality issues to be analysed (BIM, 2008). This leading edge innovative system is embedded in ESRI ArcGIS system. It enables the operation of this complex system by GIS-trained personnel with relatively minor additional training required to operate the system.

The modelling components include 2D and 3D hydrodynamic and biogeochemical models, based on DIVAST and POM, respectively. Further modelling components include ShellSIM (oyster and mussel growth model from the Plymouth Marine Laboratory), MUSMOD (mussel aquaculture modelling, Campbell and Newell, 1998), computational fluid dynamics model for a farm scale flow simulation developed by Blue Hill Hydraulics, Inc., and FARM and E2K ecological models implemented by Longline Environmental and IMAR, Portugal (BIM, 2007a). The model was designed to be used by

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industry and regulators to understand and manage better the culture of shellfish in Irish waters. Various 'what if' scenarios can be run, e.g. how reorientation of rope mussel lines impacts on flow, growth and productivity (BIM, 2007b).

Table 4.5: Overview of the UISCE modelling system

Strengths	Limitations or weaknesses
+ Modelling system includes several complex models, but is embedded within ArcGIS and can be operated by a GIS staff with some additional training. + Designed for use by industry and regulators + Can be used to run different scenarios	- Developed for use in Ireland only at the moment (but components have been used elsewhere so the framework and approach could be adapted).
Summary: The UISCE modelling system integrates multiple modelling components within a framework and was developed for industry and regulators to understand and manage shellfish culture.	

4.3. Strengths and weaknesses

Shellfish growth and production models are well developed for commonly cultured species in Europe. Based on techniques and approaches, the models have been tested and validated over many years. Further studies beyond individual growth and farm scale would be beneficial to evaluate the wider ecosystem and environmental interactions. Ecopath with Ecosim has been used to assess the ecological impact of shellfish culture on the wider ecosystem and food web. Complex hydrodynamic models would provide information on the carrying capacity of the water body to support shellfish culture. This is particularly important as shellfish culture is seen as a key aquaculture sector for expansion. Furthermore, growth models such as DEB are static and do not consider temporal or spatial elements. To understand carrying capacity, growth models can be linked to earth observation data to simulate past, current and future conditions. This is important for understanding potential impacts from climate change.

4.4. Summary and recommendations for models

Two modelling frameworks for estimation of the carrying capacity for shellfish culture will be refined and run for oyster and mussel species in TAPAS. Shellsim is a shellfish model that has been applied in many different areas throughout the world and in TAPAS it will be coupled to a hydrodynamic-ecosystem model (FVCOM) with the European Ecosystem Model (ERSEM). The other approach will couple shellfish growth DEB models to earth observation data.

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5. Nutrient retention by benthic organisms at marine fish farms

5.1. Benthic organisms at marine fish farms

Benthic macrofauna and primary producers play an important role in coastal nutrient cycles and overall ecosystem resistance to eutrophication (Lloret and Marin, 2011). Benthic macrofauna plays an essential role in the maintenance of the ecosystem's integrity by mediating exchanges and transformations of energy and materials, including nutrients, between the water column and sediments (Hansen and Kristensen, 1997; Twilley et al., 1999). Furthermore, macrobenthos production provides an important trophic transfer vehicle within the coastal ecosystem (Diaz and Rosenberg, 1995). In this way, benthic macrofauna affect coastal nutrient cycles and indirectly it could modify the functioning of macrophytes beds or diatom biofilm via their active grazing on primary producer forms and modulation of nutrient fluxes.

Macroinvertebrates seem to be responsible for certain biotic feedbacks that can ultimately modify an ecosystem's response to nutrient enrichment. Therefore, stress-induced changes to the benthos need to be understood well enough to apprehend consequential losses of vital ecosystem services. Benthic communities inhabiting close to fish farm constitute a very effective nutrient uptake and retention 'machine' that is responsible for the relatively good condition and ecological quality of the area. Nutrients entering from fish cages are effectively removed from the water column and stored in the sediments. But translocation of these excess nutrients occurs not only in the vertical axis; spatial differences in macrofaunal species composition and dominances promote a net transport of nutrients along an environmental gradient from fish farm non impacted areas where they are confined (Lloret and Marin 2009, Lloret and Marin 2011).

5.2. Models

There are few models that have been specifically designed to assess benthic macrofauna and primary producers under marine fish farms. Models like DEPOMOD and MOM have benthic sub-models/modules but they are not usually very sophisticated and may miss key interactions. BROM is an example of a more complex biogeochemical model for assessing the benthos, although at present, it is an academic model still under peer review rather than a regulatory tool. Furthermore it does not consider nutrient retention in benthic organisms.

5.2.1. Benthic sub-models of farm scale models

DEPOMOD has a benthic sub-model that predicts two benthic indices (ITI and total abundance) for a particular level of solids accumulation (Cromey et al., 2002). MOM has a simple benthic submodel. These sub-models could use indirectly to evaluate rough nutrient retention by benthic organisms.

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Table 5.1: Overview of benthic sub-models of farm scale models

Strengths	Limitations or weaknesses
+ Prediction of benthic indices	- It does not analyse nutrient retention by benthic organists
Summary: DEPOMOD and MOM predict benthic indices but they do not analyse nutrient retention by organisms.	

5.2.2. BROM (Bottom RedOx Model)

BROM (Bottom RedOx Model) is a complex biogeochemical model focusing on deoxygenation (and the nutrient cycles that impact oxygen), acidification and contamination from sediments. The documentation is currently under revision by peer review (Yakushev et al., 2016) and the code is available online for free, although some technical expertise is required to use it. BROM simulates cycles of C, N, P, Si, O, S, Mn and Fe to determine redox conditions and evaluate the carbonate system across the water column, the bottom boundary layer and the upper layer of the sediments (Yakushev et al., 2014). The model has been developed as a set of reusable components which include a stand-alone transport driver and separate modules for ecology, redox chemistry and carbonate chemistry (Yakushev et al., 2016). However the model does not consider nutrient retention by organisms.

Table 5.2: Overview of the BROM (Bottom RedOx model)

Strengths	Limitations or weaknesses
+ Free to download and use + Separate modules for ecology and chemistry	- No biological model that does not show effects of nutrients on benthic organists - Static model that does not show spatial or temporal variability
Summary: BROM is a biogeochemical model that can be used to assess deoxygenation, acidification and contamination of sediments but it do not evaluate nutrient retention by organisms.	

5.2.3. R SIAR PACKAGE

Stable isotope analysis is an increasingly important tool in the study of ecological food webs. The technique utilises the fact that biologically active elements exist in more than one isotopic form. Generally the lighter isotopic form is much more abundant in the environment than the heavier form, although their relative abundance is altered by a range of biological, geochemical and anthropogenic processes. These processes produce isotopic gradients which are reflected in the tissues of plants and animals. SIAR analyses are performed within the R environment (R Development Core Team, 2014), using SIAR (Parnell and Jackson, 2013) package, as well as R scripts made available by A. L. Jackson and T. F. Turner

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http://www.tcd.ie/Zoology/research/research/theoretical/Rpodcasts.php and http://www.esapubs.org/archive/ecol/E091/157/suppl-1.htm, respectively). SIAR calculates the distribution of possible solutions for all sources in the model. If external information is available to guide the model in the likely range of values for the dietary proportions, it can be used as a prior distribution in the SIAR modelling framework (Parnell et al. (2010). External information may arise from previous runs of the SIAR model with different data sets, sources (such as papers) which provide likely ranges, or expert opinion about the dietary proportions.

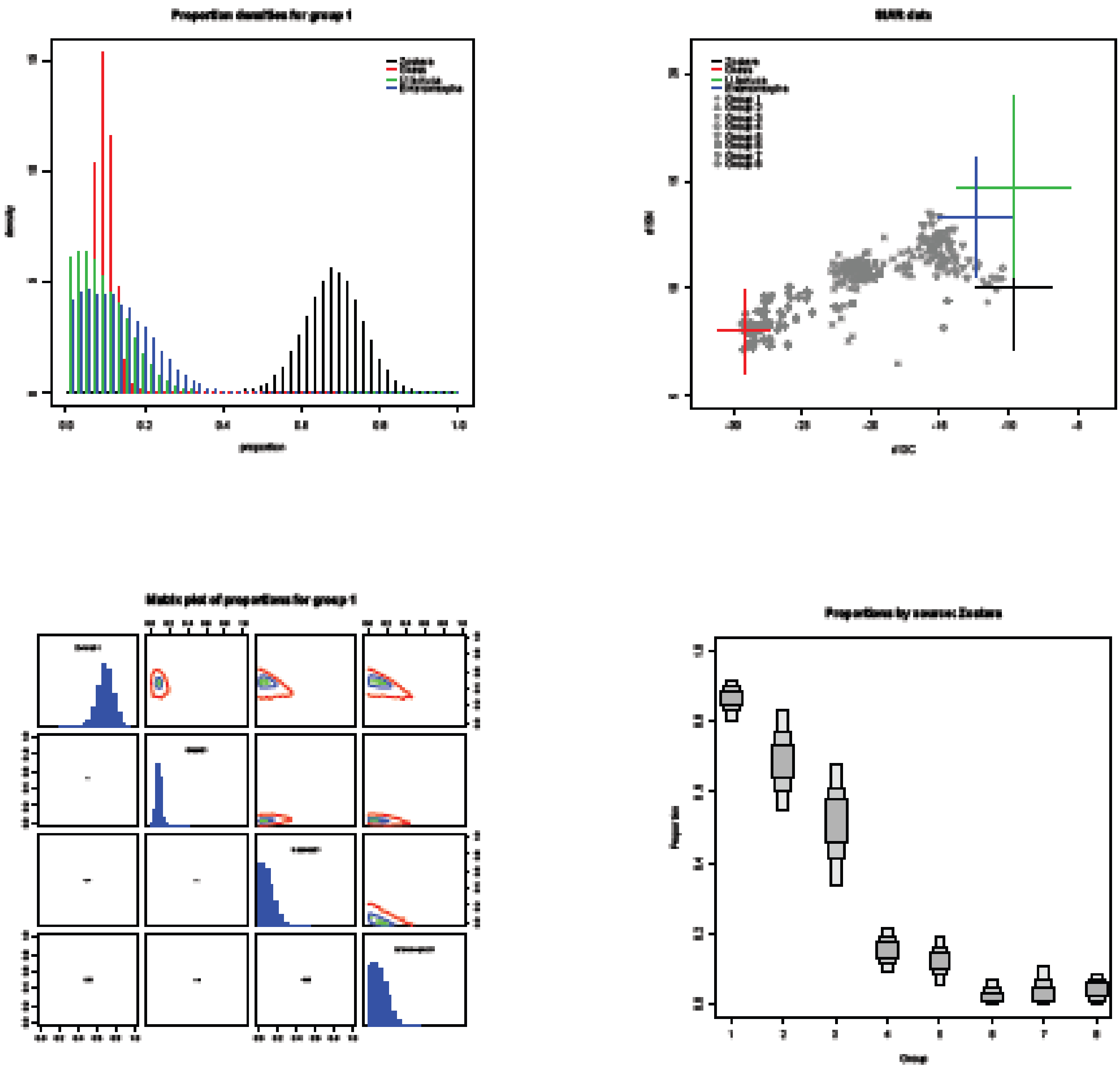

Figure 5.1. SIAR is a package designed to solve mixing models for stable isotopic data within a Bayesian framework (Inger et al., 2016).

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Table 5.3: Overview of the SIAR model

Strengths	Limitations or weaknesses
+ Free to download and use **+** Considers the trophic interaction at ecosystem level **+** Evaluation of nutrient retention by organisms	**-** The isotopic analysis can be expensive - No spatial analysis
Summary: SIBER is a free food-web modelling package that can be used to assess C and N retention in organisms but it do not analyse spatial distribution.	

5.3. Summary and recommendations for models

Nutrient retention can be analysed by specific analysis (e.g. SIAR) but there is not specific models developed for nutrient retention on marine organisms associated to fish farm. There is a need to consider the role of benthic organisms within the ecosystem, particularly under fish cages as such organisms can play an important role in nutrient cycles and resistance against eutrophication (Lloret and Marin, 2011). Spatial modelling must couple biological indices and biogeochemical analyses with nutrient retention on benthic organisms to evaluate the potential “benthic filter” capacity.

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6. Farm level models for freshwater lake systems

6.1. Freshwater lake systems

In Europe, most production in freshwater lake systems occurs in Scotland where freshwater lakes (or lochs) are used for Atlantic salmon (*S. salar*) production. There is also some culture of rainbow trout (O. mykiss) using cages in European freshwater lakes, although most production occurs in raceways or flow through systems (Wall, 2011) and some production of brown trout (*S. trutta*) and arctic char (*S. alpinus*) (Cromey et al., 2010). As noted by Wall (2011) such systems usually do not have high enough water quality for salmon. As salmon is a diadromous fish, it has a freshwater and a saltwater phase, thus, salmon aquaculture can be divided into different stages based on the biological process: production of broodstock and roe, production of fry, production of smolts and production of farmed fish (Asche and Bjørndal, 2011). In Scotland, Salmon are hatched and reared through the early life stages in land-based hatcheries. When they reach a certain size they are transferred to cage sites in freshwater lochs, where they remain there until they are 12-18 months during this time they undergo the process of smoltification and are ready for transfer to sea cages.

Phosphorus is the limiting nutrient that controls primary productivity in most freshwater lakes and reservoirs (Beveridge, 2004). It is also one of the major minerals that is required by fish in relatively high quantities (Raubenheimer et al., 2012), and is supplemented in feed (Jobling, 1994), although most diets for intensive culture contain levels that are surplus to requirements and the surplus phosphorus is excreted along or released to the environment in uneaten food (Beveridge, 2004). Total phosphorus is one of the water quality parameters that is used to classify freshwater lakes under The Water Framework Directive (WFD) 2000/60/EC. In Scotland, SEPA has classified water bodies by comparing monitoring data to the total phosphorus standard (SEPA, 2014). As fish cages in a freshwater lake will be an additional source of phosphorus loading potential impact from proposed sites and/or changes in feed or production should be modelled.

6.2. Models

Several empirical models have been developed to predict the environmental impact of increased phosphorus loadings (Beveridge, 2004). Two of the most popular models are Dillon & Rigler (1974) and OECD (OECD, 1982). However, as noted by Johansson and Nordvarg (2002) the models were not calibrated for a specific emission, and aquaculture waste may behave differently to other activities. One of the major inputs of phosphorus into a water body is from the surrounding land use, particularly agriculture. In Scotland the GIS based Plus+ model (Donnelly et al., 2011) is used to assess inputs from different types of land use in the catchment.

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6.2.1. Dillon & Rigler

The Dillon & Rigler model (1974) is a modification of a model originally developed by Vollenweider (1968, 1975) and correlates phosphorus concentration and phytoplankton growth ([Chl-a]). A mass balance model is first used to calculate the phosphorus content of wastes entering the environment from fish cages. Beveridge (2004) describes in detail a series of steps that enables use of the Dillon and Rigler model for assessment of environmental capacity. The first step involves determining the steady state concentration of total phosphorus in the lake prior to development. Then there is a need to set a maximum acceptable level of phosphorus following the introduction of fish cages. The capacity of the lake for cage culture (ΔP) is the difference between phosphorus level prior to exploitation and the desired phosphorus level once culture has been established. The capacity (ΔP) can be calculated by Equation 6.1, which can be rearranged to solve L_{fish}, the phosphorus loadings from fish cages (Equation 6.2). Once L_{fish} has been calculated, the annual 'allowable' fish production can be estimated using Equation 6.3. Beveridge et al. (2004) notes that R_{fish}, the fraction of total P waste from cages that is retained by the sediment, is the most difficult parameter to estimate.

$$[\Delta P] = \frac{L_{fish}(1-R_{fish})}{\bar{z}\rho} \qquad \text{Equation 6.1}$$

Where:

[ΔP] is total P

L_{fish} is the total P loading from the cage

$\bar{z}$ is the mean depth

R is the fraction of total P wastes from cages retained by sediments

ρ is the flushing rate

$$L_{fish} = \frac{[P]\bar{z}\rho}{(1-R_{fish})} \qquad \text{Equation 6.2}$$

$$\text{Fish production} = \frac{\text{L} \times \text{lake surface area}}{\text{P load per tonne fish produced}} \qquad \text{Equation 6.3}$$

Table 6.1: Overview of Dillon & Rigler model

Strengths	**Limitations or weaknesses**
+ Simple model that can be used to assess carrying capacity of freshwater cage aquaculture + Based on empirical measurements	- Fraction of P retained by the sediment is difficult to estimate
Summary: The Dillon & Rigler model is a simple model based on empirical measurements and used for freshwater systems to investigate phosphorus loading.	

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6.2.2. OECD

In Scotland, the OECD model (OECD, 1982) is a formal regulatory requirement when establishing or expanding a freshwater cage farm (Cromey et al., 2010). The OECD model predicts the change in total phosphorus concentration in a defined water body (e.g. freshwater lake) and can then be used to assess the impact on the trophic status of the water body (Cromey et al., 2010). Thus it can provide information for management strategies and production consents. The model can also be used for different scenarios and applications; Cromey et al. (2010) discuss three approaches; predicting the effect of an increase in aquaculture production, prediction of total phosphorus from a loch mass budget and predicting the effect of fish farming emissions before and after farming started. The model can be used to calculate annual fish cage emissions using Equation 6.4 (Johansson and Nordvarg, 2002).

$$\Delta TP = \left(\frac{\Delta TP_{in}}{1+\sqrt{T}}\right)^{b} \qquad \text{[Equation 6.4]}$$

Where:

ΔTP is the predicted effect of annual fish farm emission on in-loch concentraions

ΔTP_{in} is the predicted effect of farm emissions on inflow concentrations

T is residence time

a and b are constants from the OECD combined data set (OECD, 1982)

A study by Cromey et al. (2010) compared OECD modelled values against observed changes from a SEPA monitoring data set. The modelling approach followed the methodology used for regulatory purposes. Based on the data available and the results, Cromey et al. (2010) suggested the OECD model had limited predictive capability for assessing change in total phosphorus due to aquaculture production. However, model performance improved when used in a mass budget approach which included predictions from the PLUS model (Section 6.3) (Cromey et al., 2010), a model that considers additional inputs from land use and other point sources.

Table 6.2: Overview of the OECD model

Strengths	**Limitations or weaknesses**
+ Used for regulation in Scotland and other countries + Simple model based on empirical measurements	- Study by Cromey et al. (2010) suggested the OECD model had limited predictive capability
Summary: The OECD model is used in Scotland as part of the regulatory process when establishing or expanding a freshwater cage farm. However recent studies have suggested it is not necessarily fit for this purpose.	

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6.2.3. Plus+

The phosphorus Land Use and Slope (Plus+) is a GIS based model that is used to evaluate phosphorus concentrations in standing waters in Scotland based on land cover and point sources from the surrounding area (Donnelly et al., 2011). The model includes land use and/or land use change, as well as additional information regarding other phosphorus discharges across the catchment, for example sewage, and additional inputs from upstream are also included along with slope (SEPA, 2014). The spatial loading of phosphorus in calculated within a range of predicted maxima and minima (Fozzard et al., 1999) and for regulatory purposes Plus+ can be used to estimate current and future concentrations of phosphorus in the loch and compares the model results to a previously determined classification or regulatory standard for the waterbody (SEPA, 2014) (Figure 6.1).

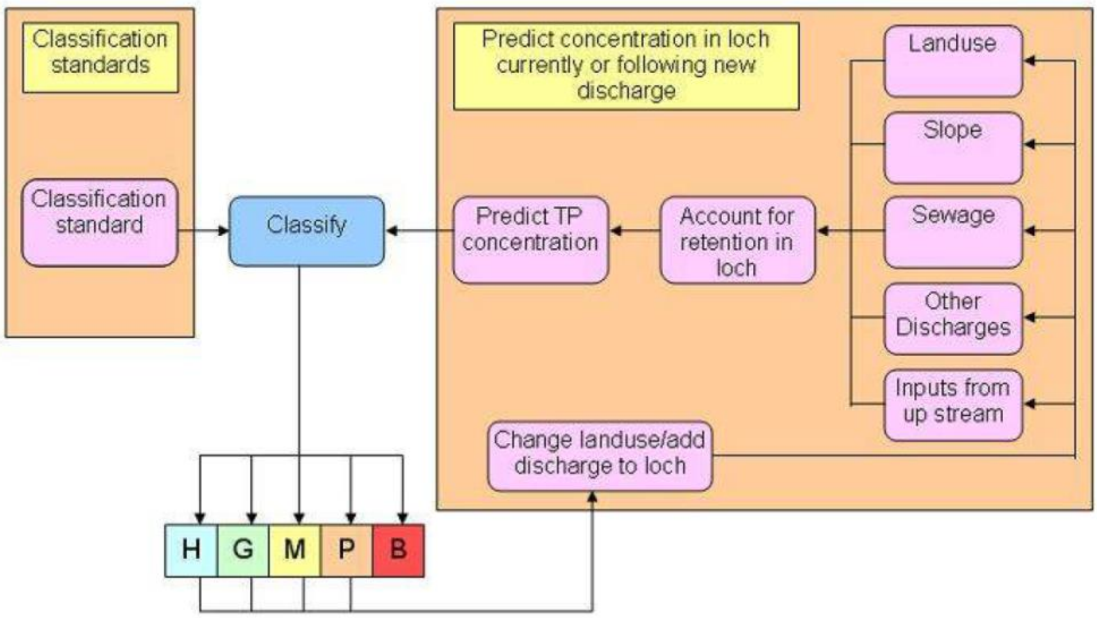

Figure 6.1: Overview of the use of Plus+ for regulatory purposes in Scotland. The classification standards refer to the WFD where H is high status, G is good status, M is moderate status, P is poor status and B is bad status (SEPA, 2014).

There are two key assumptions in the model; phosphorus loss coefficients can be used to estimate diffuse phosphorus lost from a catchment, and those coefficients can be explained by land use and slope (Carvahlo et al., 2005). The model uses a range of phosphorus loss coefficients associated with 30 land cover/land use categories (Fozzard et al., 1999; Donnelly et al., 2011). The coefficients are specific to Scotland which makes applicability elsewhere in Europe difficult unless sufficient data is available.

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Table 6.3: Overview of the Plus+ model

Strengths	Limitations or weaknesses
+ Considers inputs from the wider catchment and different types of land use + Can be used to predict effects of phosphorus loading from land use change + Supported by a user detailed user manual	- Only applicable to Scotland - Not easily accessible
Summary: The Plus+ model is used to estimate current and future concentrations of phosphorus in Scottish lochs and considers land use and land use change within the catchment as well as other phosphorus discharges.	

6.3. Strengths and weaknesses

The Dillon & Rigler and OECD models are both simple, empirically based models that are easy to use. They use simple datasets and can be calculated quickly. The OECD model is a regulatory tool in Scotland, however Cromey et al. (2010) suggest, in the current form, the model is not suitable for this purpose. Cromey et al. (2010) recommend an approach which includes the PLUS model, a model used to evaluate catchment wide inputs into the lake. However, the PLUS model has been developed specifically for Scotland and there may be limited application elsewhere. As most freshwater lake culture occurs in Scotland, broad scale applicability to other areas may not be required. However, other models like SWAT (http://swat.tamu.edu/) could also be used to simulate phosphorus inputs from the catchment.

6.4. Summary and recommendations for models

The OECD model is used for aquaculture management and regulation in Scotland (Cromey et al., 2010) and has been used in other countries including Sweden (Johansson and Nordvag, 2002). However, Cromey et al. (2010) found low performance when testing the OECD model for the consent process and recommended a need for further assessment of the approach for regulatory purposes. Thus, TAPAS will use a comparative approach to assess both Dillon and Rigler (1974) and the OECD model (OECD, 1982) for use in Scottish freshwater loch cage aquaculture.

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7. Farm level models for freshwater pond systems

7.1. Freshwater pond systems

Rainbow trout (*Oncorhynchus mykiss*) and Common carp (*Cyprinus carpio*) dominate freshwater fish production in Europe (Bostock et al., 2016; FAO Fishstat J, 2016). Major producers (>10,000 tonnes) include Italy, France, Denmark, Spain, Poland and UK for rainbow trout and Poland, Czech Republic, Ukraine and Hungary for Common carp (FAO Fishstat J, 2016). Other farmed freshwater species include roach (*Rutilus rutilus*), European eel (*Anguilla anguilla*), Silver carp (H*ypophthalmicthys molitrix*), tench (*Tinca tinca*), sturgeons (*Acipenser* sp.) and North African catfish (*Clarius gariepinus).*

The majority of fish are grown in freshwater ponds, of which there are several types, including: closed systems such as static ponds with no water exchange through the production cycle and semi-closed systems where there is some water exchange with adjacent water bodies, e.g. flow-through ponds (Appleford et al., 2012). Most ponds have a dual functionality; contain the cultured animals and treat wastes (Tucker and Hargreaves, 2012), thus farmers need to manage production to ensure nutrient build up is minimised. Intensification is limited by the waste assimilation capacity of the pond ecosystem and further intensification is only possible if wastes are treated outside of the pond, for example discharging wastes to other aquatic systems nearby (Tucker and Hargreaves, 2012). However, discharging nutrient rich wastes directly into a receiving water body may also have adverse impacts on that ecosystem so it is important to monitor, manage, and regulate such activity where necessary.

An alternative to traditional pond culture is a recirculating aquaculture system (RAS), an intensive system, designed to minimise water consumption by re-using water that is treated by mechanical, biological, chemical filtration or other means (Murray et al., 2014). RAS are considered a way of meeting the growing demand for food in a sustainable manner as they provide opportunities to reduce water use and there is improved waste management and nutrient recycling (Martins et al., 2010). However, compared to simpler pond systems, investment and operational costs are high and there are additional challenges associated with technical complexity which threaten the profitability of such systems (Dalsgaard et al., 2013). Nevertheless, as the need to produce more food increases, sustainable aquaculture systems are required and it is likely that more companies will use RAS. Denmark is considered one of the pioneering countries with regard to development of both national and international technology (Dalsgaard et al., 2013), and is the country with the most RAS grow out systems in Europe, followed by The Netherlands (Martins et al., 2010).

Production and carrying capacity of a pond will depend not only on the type of pond, but also the biochemical properties of the water supply, farm management techniques (such as stocking density and feeding regime), and release of effluents. The processes within the pond must be characterised and assessed as a build-up of nutrients could affect water quality, fish health and overall quality of the product. Thus there may be economic impacts, as well as biological and environmental, if the carrying capacity of a pond is exceeded. Furthermore, potential impact on the surrounding environment and/or receiving water bodies must also be considered, as effluents contain nutrients,

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organic matter and suspended solids (Boyd and Tucker, 1998). However, even in a simple pond system, effluents are not always directly released into the environment and there may be mitigation methods in place such as sedimentation ponds or filtration systems.

7.2. Models available

Compared to marine fish culture systems there are fewer examples of freshwater pond models for Europe, particularly proprietary models, that are available for use by farmers and/or regulators. Nevertheless, there are several modelling approaches that can be used and modelling methodologies from other areas (e.g. models for fish or shrimp ponds in Asia or marine fish culture systems) can also be adapted. As waste remains in the culture system it is often useful to use models with a temporal element. Dynamic models consider how a system changes over time (Ford, 1999) so are useful to evaluate production cycles within aquaculture systems. They are particularly useful for pond aquaculture as they can simulate nutrient flows over time and evaluate the risk of nutrient build up, taking into account the different biological, farm management and environmental conditions. To achieve this, bioenergetic/growth models can be used to simulate production and coupled to a model (e.g. mass balance) to determine nutrient output.

7.2.1. Bioenergetics/growth models

To understand the production cycle within ponds it is often necessary to use bioenergetic/growth models to assess growth. These models can then be coupled to another model(s) to consider nutrient cycles and there are several different approaches from simple, thermal-unit growth coefficient (TGC) (Iwama and Tautz, 1981) to more complex, DEB (Kooijman, 2009) . Bioenergetics focuses on energy intake, transformations and losses to the environment and can be used as a framework to investigate the relationship between feeding and growth of fish, subject to different environmental conditions (Jobling, 1993).

The TGC model is one of the most popular and widely used models for growth prediction and production planning, largely due to the simplicity and flexibility of the approach (Jobling, 2003). However as discussed by Jobling (2003) there are several assumptions within the model that users should be aware of; growth of the fish increases steadily with increasing temperature, growth in length is constant over time and the ratio of weight (W) and length (L) is $W \propto L^3$. The TGC can be used to calculate growth rate for the fish and then coupled to other models/sub-models to estimate nutrient flow and waste inputs into the environment. An example of this is the model developed by Cai et al. (2016) to estimate nitrogenous loadings from

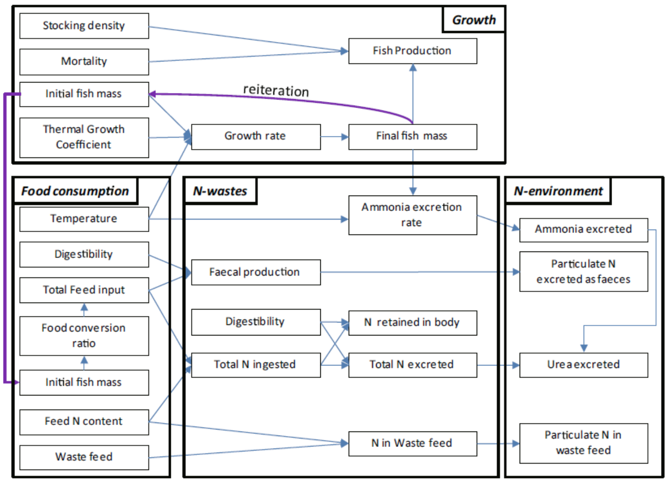

Figure 7.1: Model integrating thermal growth coefficient with other components, including a mass balance, to estimate nitrogenous loadings from large yellow croaker cages (Cai et al., 2016)

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Large yellow croaker (*Larimichthys crocea*) in a coastal area in China (Figure 7.1).

Another bioenergetic model based on TGC was integrated with several other components to produce the Fish-PrFEQ software, developed by the Onatrio Ministry of Natural resources, which is used to estimate growth, feed requirements and waste outputs of fish aquaculture (Cho and Bureau, 1998). Fish-PrFEQ has been modified and used as an environmental management tool for land-based trout farming in France (Papatryphon et al., 2005). This highlights the flexibility of the TGC model as it can be used for any fish culture system (cages and ponds). However, the fish species must have the suitable length-weight ratio and users should be aware that it is not suitable for use outwith certain temperature ranges and there will be errors if used for fish that are experiencing marked changes in body condition (Jobling, 2003). Similar approaches to TGC include the Specific Growth Rate (SGR) and the Daily Growth Coefficient (DGC). Neither SGR or DGC consider temperature (Iwama and Tautz, 1981), however both have been used in aquaculture studies: SGR (Roque d'Orbcastel, 2009; Munro, 2014), DGC (Kim et al., 1998).

Table 7.1: Overview of TGC models

Strengths	Limitations or weaknesses
+ Simple and flexible model + Can be coupled to other models such as mass balance to calculate nutrient use and waste inputs	- Based on several assumptions - Not suitable for all fish species
Summary: The TGC is a simple model that can be used to estimate fish growth and then coupled to other models to estimate production and nutrient loadings.	

The TGC model represents are relativity simple approach, in contrast to the more complex DEB approach which is more theoretical and abstract than the “traditional” bioenergetic models (Nisbet et al., 2012). Differential equations are used to describe the rates at which an organism assimilates and utilises energy from food for maintenance, growth, reproduction and development (Nisbet et al., 2000). The DEB approach is more complex than a mass balance. It is difficult to estimate DEB parameters as many cannot be measured directly (van der Meer, 2006). However, depending on the application, not all parameters are needed and a subset can be used (Lika et al., 2011). Lika et al. (2011) developed the “covariation method” to estimate parameters from data and have also collated parameters and data for over 300 animal species in the add_my_pet collection (http://www.bio.vu.nl/thb/deb/deblab/). Nevertheless, data is not available for all aquaculture species, so further laboratory experiments may be required, potentially limiting any application of this method.

The DEB approach is becoming increasingly more popular in biology and there have been several applications for aquaculture, primarily shellfish (Barillé et al., 2011; Handa et al., 2011; Thomas et al., 2015) but also fish (Serpa et al., 2013b) and IMTA (Ren et al., 2012; Lamprianadou et al., 2014). Serpa et al. (2013b) developed a DEB model to simulate the growth of white seabream (*Diplodus sargus*) and gilthead seabream (*Sparus aurata*) in semi-intensive ponds. The DEB was also coupled to

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a biogeochemical model that simulates nutrients in the water column and sediment (Serpa et al., 2012), to consider different management scenarios such as an increase in stocking density, changes in water exchange rates and changes to feed (Serpa et al., 2013a). DEB is more complex than the TGC but in turn it allows a more detailed examination of fish growth across the entire life cycle.

Table 7.2: Overview of DEB models

Strengths	Limitations or weaknesses
+ Simulates fish growth across the entire life cycle + Can be coupled to other models such as mass balance to calculate production and nutrient loadings.	- Data requirements and data availability may be an issue. - More complex than other growth models
Summary: DEB models are more complex than other growth models, however if the required data is available they can be used to simulate growth across the entire life cycle and coupled to other models to estimate production and nutrient loadings.	

7.2.3. Mass balance

One of the most common methods for modelling the nutrient dynamic within any aquaculture system is a mass balance approach. Based on the principle of mass conservation where matter entering a system must either accumulate or leave the system, the mass balance equations use data on feed, food conversion ratios (FCR), digestibilities and faecal composition to estimate wastes, and thus the nutrients, entering the environment (Beveridge, 2004). A comparison between mass-balance models and hydrological monitoring for characterising waste output from flow through trout farms in France and found high correlation for both total nitrogen and total phosphorus (Aubin et al., 2011). Aubin et al. (2011) suggest that the mass-balance approach is a cost-efficient method for both farmers and regulators as it is less labour and data intensive than hydrological monitoring and has similar results. Many other studies have also found that the mass-balance approach is a useful and robust method of nutrient modelling for freshwater aquaculture systems (Knösche et al., 2000; Paratryphon et al., 2005; Roque d'orbcastel et al., 2009).

The advantage of the mass balance approach is that it can be as simple or as complex as required by the user, providing the necessary data is available. Furthermore, it is easy to adjust or change parameters to explore alternative scenarios such as different types of supplementary feeds (Hlavác et al., 2015). However, on its own, a mass balance does not provide information on the fate or impact of wastes. Nevertheless, a mass balance can be coupled to other models such as bioenergetic models that simulate growth and/or hyrodynamic models that simulate waste dispersion. The use of other models together with a mass balance provide a more holistic evaluation of the system. Consequently, a mass balance is often a fundamental component in aquaculture models, for example, the FARM model uses a mass balance within the overall model structure to simulate nutrients in the system (Ferreira et al., 2007).

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Ecopath with Ecosim is a trophic mass-balance model which is used to assess energy flow through ecosystems and the relationships and interactions between different species. Zhou et al., (2015) used Ecopath with Ecosim to characterise the trophic structure and ecological interactions in a grass carp (*Ctenopharyngodon idellus*) farm pond. The model was used to assess the productivity of the pond system and results suggested a polyculture system would be more efficient, exploiting the potential productivity of the pond and increasing fish outputs (Zhou et al., 2015). For a herbivorous species such as grass carp that is dependent on food from the ecosystem, it is useful to characterise the food web using Ecopath with Ecosim, however it is less appropriate for fed species.

Table 7.3: Overview of mass balance approach

Strengths	**Limitations or weaknesses**
+ Simple, quick to run and very easy to adapt + Can be very detailed if appropriate data is available and the system requires it.	- Does not consider fate or impact of nutrients but can be coupled to other models -
Summary: The mass balance approach can be used to calculate nutrients entering the aquatic system. It is a popular approach for aquaculture largely due to the simplicity and ease of use.	

7.2.4. Recirculating aquaculture system (RAS)

An option to reduce environmental impacts associated with feed aquaculture are recirculated aquaculture systems (RAS) established in land-based facilities, where fish waste products such as faecal material and ammonia are sequestered using advanced wastewater treatment technologies prior to returning treated water back to fish tanks. Besides local environmental benefits production in RAS systems saves water, allows to control temperature, the hygienic and sanitary state of fish by preventing introduction of pathogens. Despite such advantages RAS only account for a minor proportion of the EU inland aquaculture, primarily due to high investment and operational costs, and significant risks for yield decrease or harvest loss due to equipment failure or insufficient understanding and control of the individual processes and their interdependence (Ebeling and Timmons, 2012; Wik et al. 2009).

In RAS fish growth depends on temperature, pH, Total Ammonia Nitrogen (TAN), NO_2, and feeding rate and quality of feed. Although not trivial, predicting/modelling fish growth is less challenging than predicting and controlling the water treatment processes because of several tightly or loosely coupled feed-back processes involved (Fig. 7.2). Numerical models are widely applied in RAS design, planning and monitoring (Wik et al. 2009, Halachmi 2012, Pedersen et al. 2012) - many of which builds on wastewater treatment models (Henze et al. 2008, Vanhooren et al. 2001).

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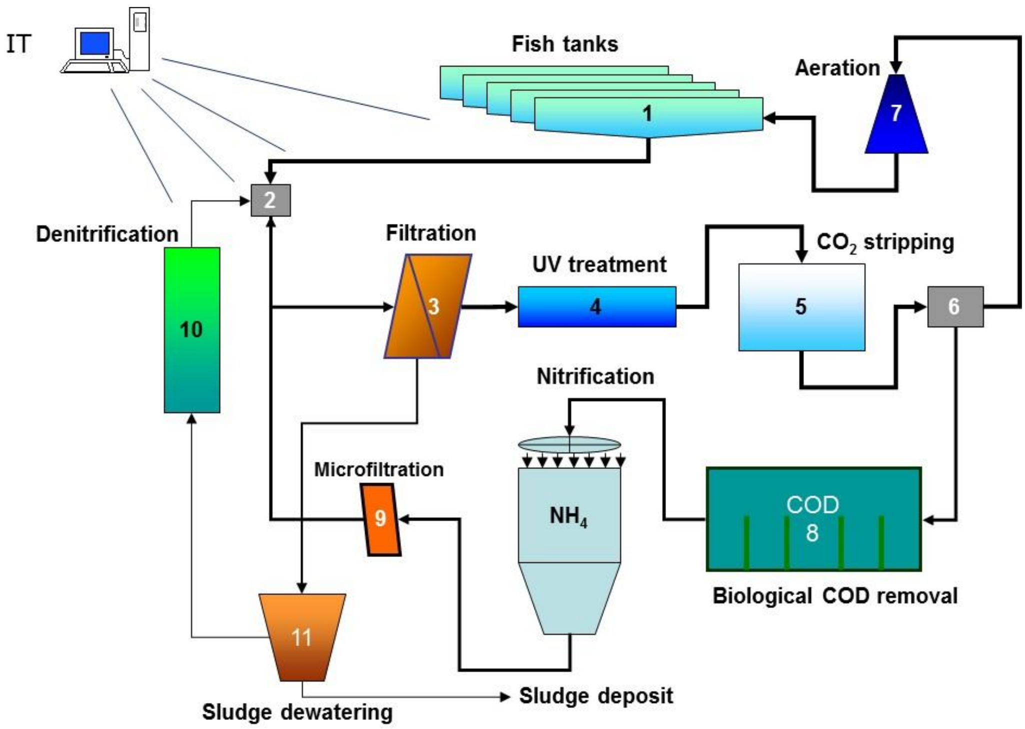

Figure 7.2: Schematic flow diagram of water treatment processes in RAS (after K. Janning, DHI)

Despite all challenges, commercial RAS farms operating for more than a decade are the living proof of the viability of the concept, which are also documented in comparative studies showing identical growth and feed-conversion-ratio in rainbow trout farmed in flow-through systems and RAS (d'orbcastel et al. 2009; Pedersen et al. 2012). Remaining issues to reduce operational costs of RAS are optimization of movement of water, container design, efficiency of filters etc. (Plesner et al. 2011, Pedersen et al. 2013, Prehn et al. 2012, Suhr et al. 2010). To assist such optimization dynamic simulation models encompassing all system elements (see Fig. 7.2) are required.

7.2.5. Other models

Depending on the type of pond system and the surrounding environment and activities, it may also important to consider potential impacts on receiving water bodies from pond outfalls. Initial dilution and mixing zone models such as ELSID, Visual Plumes and Cormix can be used to simulate discharge plumes from point sources (SEPA, 2013). These models have been developed by regulatory authorities (ELSID - National Rivers Authority, UK and Visual Plumes and CORMIX - United States Environmental Protection Agency). However, they are generic models that are used for any point source discharge and are not aquaculture specific. Trieu and Lu (2014) developed a numerical model to assess the direct discharge of total dissolved and particulate nitrogen and phosphorus from pond and cages to rivers.

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7.3. Strengths and weaknesses

Dynamic models are advantageous as they can evaluate production and environmental impacts throughout the life cycle. This is key for aquaculture as it is not a static activity so must be considered across a temporal scale and is particularly important for pond culture where nutrients may build up within the culture system, potentially affecting production as well as the health and welfare of the fish. A useful approach is the integration of bioenergetic models that consider growth, with mass balance models that consider potential waste outputs throughout the production cycle. However, some bioenergetic models such as DEB are complex and require a lot of data that is not readily available. An advantage of DEB models is that they can be used across the entire life cycle, nonetheless if the pond is only used for grow out then the added complexity may not be necessary and a simpler approach can be employed.

Farms usually have multiple ponds but models often focus on a single pond. Munro (2014) developed models within the Powersim modelling software package that considered farm level as well as the individual ponds. This may be a useful approach for management and regulation as multiple ponds may be farmed differently even within one farm so modelling one pond and scaling up may not be appropriate. Furthermore, it can also incorporate potential methods and techniques such as sedimentation ponds that are used to reduce aquaculture wastes in farm outflows.

Regulators will focus on the potential outflow and discharges from a pond or farm into a receiving water body. Although more complex models can be used to simulate the fate of discharge from a pond outfall, it is often enough just to use a simple mass balance approach that can calculate the amount of nutrient entering the environment. This approach is recommended by several studies (Paratryphon et al., 2005; Aubin et al., 2011) and can be used in areas where regulators determine nutrient limits in effluents (e.g. certain areas in France (Paratryphon et al., 2005)). However, when establishing and reviewing thresholds and limits, regulators may have to use more complex models to understand the environment and thus the potential fate of wastes, to ensure the regulatory limits are appropriate.

7.4. Summary and recommendations for models

TAPAS will develop dynamic models based on the approach used by Munro (2014) for pond culture in Asia. The models will be used to evaluate nutrient flow and carrying capacity in freshwater pond systems and will also be adapted for fully recirculated aquaculture (FREA) systems. This will allow a comparison between the culture systems and will provide useful information for farm management and regulation.

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8. Spatial models

8.1. Spatial site selection and carrying capacity

Spatial issues affect and influence many processes and decisions in aquaculture. From the initial identification of an area for development to establishing international trade opportunities, there are spatial elements across all areas and scales. Naturally, site selection and carrying capacity are fundamentally spatial as spatial attributes can determine development, production, environmental impact and socio-economic consequences. However, spatial issues will vary depending on the species, system and type of culture; for example, marine cages that are open to the environment will have different interactions and impacts than land based recirculating systems. Furthermore, there may also be indirect spatial issues that are associated with the wider value chain such as the supply of goods and services.

Models must focus on the spatial issues associated with aquaculture at appropriate scales and resolutions. Large scale models, at global or regional level can use coarser resolutions but this will be insufficient for local or farm level models. There are advantages to assessment across multiple scales, local level models can be used to assess environmental impact and determine production capacity, while larger scale models can be used at a more strategic level for planning and development of the sector. Identifying study area boundaries is often difficult as geographical features and processes do not adhere to political or administrative divisions. As spatial models can have broad applications and many different purposes it is important to define the scope and aim of the model as well as the intended function to ensure appropriate use by stakeholders. For example, a site selection model may identify areas where aquaculture can physically be located (sufficient depth, good access etc for cages) but it might not include variables that can determine amount or quality of production.

8.2. Models

Spatial models have become popular tools for aquaculture site selection since the first applications over 25 years ago (Kapetsky et al., 1987; Meaden, 1987; Ali et al., 1991; Ross et al., 1993). Over the years as technology and data have improved the models have been applied to many different systems and species throughout the world (Nath et al., 2000; Ross et al., 2009; Ross et al., 2013). The physical suitability of a location to support aquaculture production is one aspect of site selection, but spatial models can also be used to explore spatio-temporal issues such as climatic events, assess potential socio-economic issues and can be used for planning and management at a wider scale with multiple activities and stakeholders, e.g. marine spatial planning.

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8.2.1. Site selection and physical carrying capacity

The suitability of a site for aquaculture will be influenced by many factors, some of which are highlighted in Box 8.1. This is far from an exhaustive list and it must be acknowledged that criteria and their importance will vary depending on the type of system, species being cultured and the areas under evaluation. Criteria can be evaluated individually, however a suitable site must be located in areas where all relevant factors meet certain requirements. A more efficient method is the use of Geographic Information Systems (GIS) to develop spatial models that combine and trade-off factors to evaluate the suitability of a site qualitatively and quantitatively.

Box 8.1: Examples of site selection criteria

- Bathymetry
- Sediment type
- Wave height
- Currents
- Productivity
- Water quality
- Water supply
- Soil type
- Slope
- Topography
- Cost of land
- Electricity
- Access

A common method of developing aquaculture site selection models is the use of a multi-criteria evaluation (MCE). MCE is a modelling approach that can be used to analyse complex trade-offs between alternative choices (Carver, 1991). Input data are factors important for site selection (e.g. criteria included in box 8.1) and are reclassified to a common classification scheme. There are several methods of reclassifying data including Boolean, user defined hard classification and fuzzy. Boolean classification is the simplest method where values are considered either suitable or not suitable (score of 1 or 0). The Boolean output is easy for decision makers to interpret as the binary output gives a clear choice, however in reality some areas will be more suitable than others so it may be insufficient for many purposes. User defined hard classification is where the user reclassifies the data into distinct classes is one of the most commonly used reclassification schemes in aquaculture site selection studies (Giap et al., 2005; Salam et al., 2005; Hossain et al., 2009; Ross et al., 2011). The advantage of this approach is that it is easily interpreted by decision makers and provides more detail than the Boolean classification as there are a range of suitability classes. However, there may be uncertainty associated with hard boundaries (Eastman, 2012) as thresholds for some parameters may not be clear, particularly between several suitability categories. An alternative approach is fuzzy classification where transition is gradual between suitable and not suitable (Zadeh, 1965; Eastman, 2012). For regulatory purposes, fuzzy classification may not provide enough support for decision makers as the results can be more difficult to interpret without defined categories.

Within model development and decision making there are often variables and factors which have different levels of importance (Nath *et al.,* 2000). Weights can be applied to variables to specify the importance of the factors relative to others included in the assessment (Carver, 1991). As discussed by Nath *et al.* (2000) weighting can be subjective and model developers must try to use an objective approach to assign weights. The use of expert opinion to help assign weights can be an advantage but it must also be noted that experts with different backgrounds and agendas may have differing views on the weights (Nath *et al.,* 2000). This can lead to conflict over model development and uncertainty in the final results. In some cases, it may be necessary to produce multiple models that

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consider different weights and thus provide alternative planning scenarios for decision makers depending on the overall aim of the work.

An advantage of this approach is the ability to consider biological, environmental and socio-economic factors within one model framework. This is highlighted by the site selection model developed by Salam et al. (2005) for carp aquaculture in Bangladesh (Figure 8.1). As site suitability is dependent on a number of criteria it is important to use tools such as GIS that can analyse the information in a holistic way. However, it must also be noted that model structure and the way data is combined will influence the results and there is a danger that important variables can get lost in the noise of others if there are too many parameters to consider.

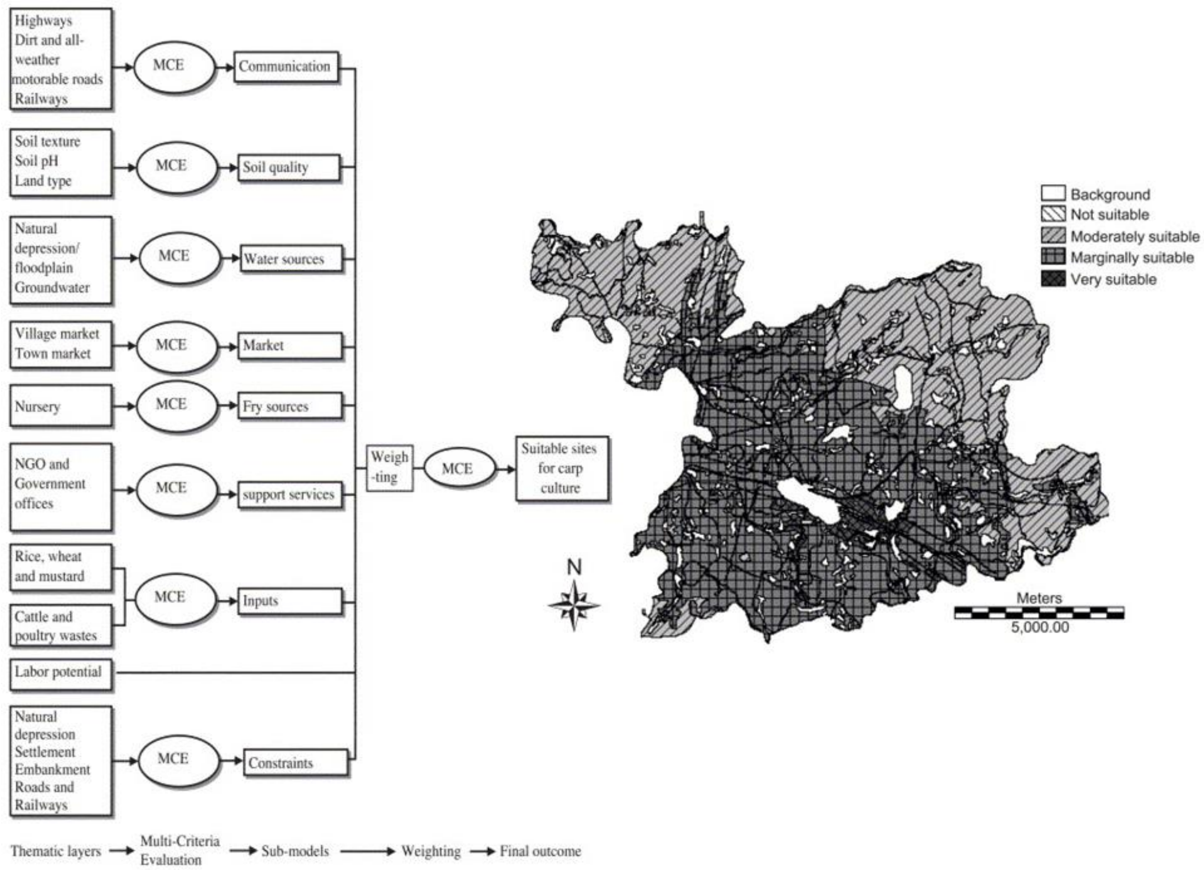

Figure 8.1: Suitable sites for carp farms in Barhatta Upazilla, Bangladesh and the structure of the model (adapted from Pérez et al., 2005)

Other examples of GIS models developed using the MCE approach include: offshore floating marine cages for seabream (*S. aurata*) and Sea bass (*D. labrax*) in Tenerife (Pérez et al., 2005), mangrove oyster (*Crassostrea rhizophorae*) raft culture in Venezuela (Buitrago et al., 2005), Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Japan (Radiarta et al., 2008), land suitability giant prawn (*M. rosenbergii*) in Bangladesh (Hossain and Das, 2010), tilapia (*O. niloticus*) cages in a freshwater

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reservoir in Mexico (Ross et al., 2011) and brackish water aquaculture development in Iran (Hadipour et al., 2015).

8.2.2. Spatio-temporal issues for site selection

The suitability of a location may change over time, thus it is also important to consider both short and long term issues that may impact a site. Temporal data can be easily incorporated into spatial models and some studies have used seasonal measurements within their analysis (Longdill et al. 2008; Silva et al., 2011). The seasonal variability of site suitability is further highlighted in a study by Ross et al. (2011) which found significant differences of water availability in a reservoir in Mexico due to a large drop in water level between the wet and dry season. Consequently, there were significant seasonal differences for both the availability and suitability of areas for cage culture (Ross et al. 2011). If the model used one single output, then this seasonal variation could have been missed and the final model output would over estimate or under estimate the availability of suitable sites in the dry and wet season respectively. This stresses the importance of incorporating seasonal measurements, where possible, into site suitability studies.

Infrequent events and extreme conditions can also influence the suitability of a site for aquaculture. Falconer et al. (2013a) used a worst-case scenario approach to model the suitability of coastal and offshore sites for selected cage types. This included factors such as the maximum significant wave height, conditions that may be rare but they could damage equipment and endanger the fish if cages are installed in unsuitable locations. Decision makers can use the model to select sites and determine the most appropriate cage type to use. However, it is important to note the model does not predict what will happen and when, instead it indicates what could happen.

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Analysis of time-series data can provide valuable information for both present day and future planning and management for the sector. Liu et al. (2014) used remote sensing data to assess the spatio-temporal suitability of aquaculture sites from 2003 to 2012. This also included climatic events such as the winter East Asian Monsoon and El Niño/La Niña, which is useful for predicting suitability or identifying risks for future events. Remote sensing data can also be used to identify areas at risk of natural hazards. Handisyde et al. (2014) adapted an approach previously used by Sakamoto et al. (2007) to identify areas of surface water on the floodplain of the Rio Paraná, Argentina, from an 11-year time series. This allowed estimation of the risk of flooding (Figure 8.2) providing useful information for existing and future aquaculture developments. Decision makers can identify areas that should or should not be used for development and/or areas that may need require additional flood mitigation methods and support.

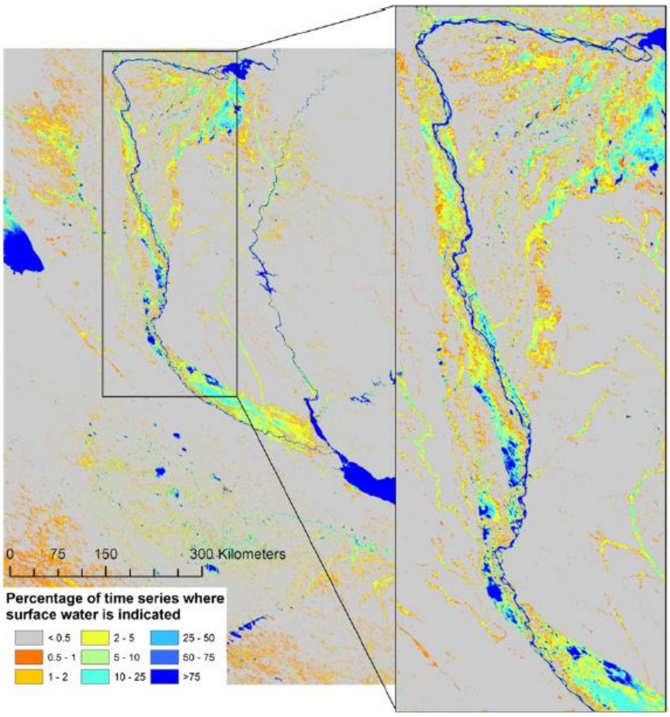

Figure 8.2: Percentage of time series where surface water flooding is present derived from cloud free images for the floodplain of the Rio Paraná, Argentina (Handisyde et al., 2014)

The long-term impacts from climate change are difficult to predict, but spatial models can identify areas that might be more vulnerable than others. Handisyde et al. (2006) used a global scale GIS model based on the concept that vulnerability is a function of exposure to climate change, sensitivity to climate change and adaptive capacity. The advantage of this approach is that it includes not only exposure and sensitivity but also adaptive capacity and thus it can be used to prioritise countries that may need support in the future, targeting areas most in need. Although global assessment is essential, more detailed analysis at a local scale is also necessary to assess site suitability and assist future policy, planning and regulation at a national and regional level. Saitoh et al. (2011) used GIS, satellite data and the Intergovernmental Panel on Climate Change (IPCC) scenarios to assess the potential impact of climate change on site suitability for Japanese scallop (*M. yessoensis*) aquaculture in Japan. The results showed a decrease in the most suitable areas for aquaculture with increases in sea surface temperature (Saitoh, 2011). This information can be used in adaptation plans to identify future strategies which can consider species, site and systems that are most suitable for the changing conditions.

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8.2.3. Social carrying capacity

Spatial models can also consider social and economic factors. Market accessibility is commonly used as a factor in site selection models. GIS software modules can be used to calculate the “cost” (financial, time, energy etc.) of using transport networks which may also have implications for logistics of a farm operation. van Brakel and Ross (2011) used a GIS based spatial Bayesian probability model to simulate market accessibility and estimate the number of poor people who could potentially benefit from improved market access under four different scenarios. Such analysis provides important information for planning and management of the sector and the livelihoods of many people.

Spatial models can also be used to provide a more objective approach to social aspects that may otherwise be difficult to quantify. The visual impacts of aquaculture are often controversial and in some countries, particularly in Europe, they must be assessed as part of the planning process (Falconer et al., 2013b). Falconer et al. (2013b) developed a GIS-based modelling approach to consider the visual impact of coastal aquaculture. In addition to potential visibility the models also considered sensitivity of the area to visual change by incorporating landscape and seascape sensitivity models. Visual impact can also be included in a multi-component site selection process, for example, Pérez et al (2005) included viewshed (area visible) from tourist sites and beaches within a site selection study for fish cages in Tenerife, integrating social, physical and environmental factors in one model (Figure 8.3).

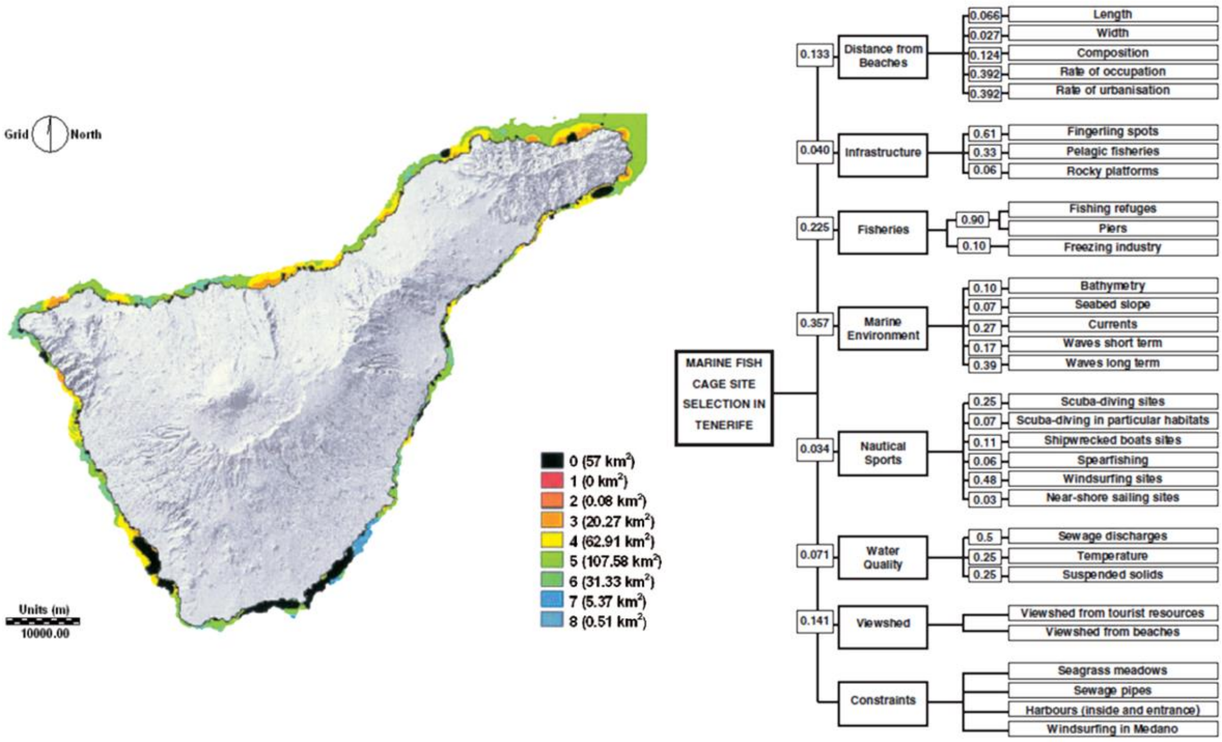

Figure 8.3: Suitability map, masked to depths of 50m for siting fish cages in Tenerife and the structure of the model (adapted from Pérez et al., 2005)

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8.2.4. Spatial planning with multiple stakeholders

Any development or expansion of aquaculture must consider other users and activities in the area and vice versa. Thus management of an area often requires co-ordination between multiple stakeholders who all have different and competing interests, e.g. marine spatial planning (MSP) and integrated coastal zone management (ICZM). Use of space and natural resources will usually involve some degree of trade-off and even a simple decision could have complex consequences for individual farmers and the community. Salam et al. (2003) used GIS models to evaluate the suitability of southwestern Bangladesh for culture of mud crab (*Scylla serrata*) and the giant tiger shrimp (*Penaeus monodon*). This is a useful approach as it presents the choices in a clear and easy to understand manner, however implications to the wider value chain can be difficult to include.

The environment should not and cannot be exploited solely for economic or human benefit, there must also be consideration of biodiversity. Several software packages are available to support conservation planning, including Marxan, Zonation, C-Plan and ConsNet (Moilanen et al., 2009). Marxan (www.uq.edu.au/marxan/) is one of the most popular and has been used for both terrestrial and marine spatial planning throughout the world. Mazor et al. (2014) used Marxan as a tool to examine planning scenarios for the Mediterranean waters of Israel, which would allow protection of marine biodiversity and other activities and potential threats to conservation, including commercial fisheries, hydrocarbon exploration, shipping, recreation and aquaculture. The results not only examine the trade-offs between different activities but also different planning scenarios and zoning schemes of varying complexity (Mazor et al., 2014). As noted by Ball et al. (2009), Marxan can also be used to solve a range of spatial prioritization problems beyond protected areas.

8.3. Strengths and weaknesses

Advantages of GIS include the ability to handle a vast range of data sources, resolutions and time-series data (Ross et al., 2009). Furthermore, as GIS can produce multiple scenarios and present spatial information in a visual format that is easy for all stakeholders (Corbin and Young, 1997; Longley et al., 2005) to understand it is a valuable tool for site selection. However, as noted by Ross et al. (2009), data collection can be challenging and often the most time consuming part of model development is establishing the spatial database.

Table 8.1: Use of spatial models for aquaculture site selection

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Strengths	Limitations or weaknesses
+ Can combine different data sets (environmental, social, biological) + Can assess both spatial and temporal data + Can cover multiple scales in one model	- Experts may disagree over data reclassification, weightings and model structure. - Often there is no single “correct” answer which can lead to uncertainty. - Can be difficult and time consuming to collect and process data.
Summary: Spatial models are useful tools for site selection and carrying capacity. There are many different approaches and frameworks that can be used to integrate biological, environmental and socio-economic information across different scales and resolutions.	

8.4. Summary and recommendations for models

Many of the most important issues associated with site selection and carrying capacity are spatial, thus tools and models are useful to support management and regulation of the industry. Aguilar-Manjarrez et al. (2008) highlight the importance of spatial models in implementing the ecosystem approach to aquaculture. TAPAS will develop spatial models for individual locations to determine the physical capacity and other relevant spatial issues. Multi-component models can be developed which provide a more holistic overview of the system(s) at a local and wider scale. The model frameworks will be transparent and adaptable, allowing application to other areas. This is particularly useful for stakeholders as it will allow a more streamlined process for planning and management.

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