J. Appl. Ichthyol. 17 (2001), 163–172
ISSN 0175-8659


Received: January 26, 2001
Accepted: March 26, 2001



# Use of hydrodynamic and benthic models for managing environmental impacts of marine aquaculture

By A. Henderson[1], S. Gamito[2], I. Karakassis[3], P. Pederson[4] and A. Smaal[5]

[1]*Scottish Environment Protection Agency, Redwood Crescent., East Kilbride, Glasgow G76, Scotland;* [2]*Faculdade de Ciências do Mar e do Ambiente, University of Algarve, Faro, Portugal;* [3]*Institute of Marine Biology of Crete, PO Box 2214, Heraklion 71003, Greece;* [4]*Ministry of Food, Agriculture and Fisheries, Institute of Fisheries Research, The North Sea Centre, PO Box 101, DK-9850 Hirsthals, Denmark;* [5]*Rivo DLO, Centre for Shellfish Research, PO Box 77, 4400 AB Yerseke, The Netherlands*

## Summary

Regulation to minimize impacts from aquaculture is of key concern in coastal zone management for the sustainability of the industry and the receiving environment. Market and consumer forces are presently driving much of this regulation and its implementation. Mathematical modelling can provide the tools for planning and monitoring as well as regulation, and a number of countries have well-developed policies and procedures in place which utilize modelling tools. The main impacts currently modelled are nutrient enhancement, organic waste deposition and the dispersion and deposition of medicines and chemicals. The release of these wastes is influenced by species- and site-specific characteristics, as well as culture and husbandry techniques. The modelling process requires consideration of definitions and limitations; standards for model development including clear objectives and justification; good technical description; use of good and appropriate data; calibration; validation; sensitivity analysis; quality assurance; auditability and consideration of the operational needs of the user, the grower and/or the regulator. Models should have simplicity and clarity; be fit for purpose; be open to scrutiny; be accessible, user-friendly and be used with caution. Current models are considered to be limited in scope but do cover the main hydrodynamic and particulate processes. The regulation and monitoring of finfish aquaculture involving the *direct* use of models is apparently restricted to relatively few countries where they are involved in setting holding capacity, the licensing of medicines and for assessing site applications. Different approaches have been developed in different countries as required. In contrast, many countries do make considerable *indirect* use of modelling techniques within the regulation process. With respect to shellfish, models are in current use to predict and optimize exploitation capacity but there is scope for studying nutrient flux, habitat degradation and deposition below suspended systems. Future developments for finfish need to better address the main question of holding capacity or exploitation capacity in relation to nutrients and medicines release, including whole water body/regional impacts. The relationship and predictability of toxic algal blooms remains some way off. Modelling the complexities of degradation, resuspension and the effect of the scavenging process on the transport of in-feed medicines is required. Keys to future developments across Europe include accessibility, setting of Environmental Quality Standards or targets, training and support for users, resources and structured research.

## Introduction and background

The use and development of models in a research context is an advanced science in many parts of Europe. Their applied use in studies relating to water and particle movement in, for example, a pollution control context for dispersal of pathogens, for the prediction of impact scenarios in estuaries or coastal waters as a system design aid and their role in hydrodynamic investigations relating to discharges, is well accepted and continues to grow.

Models can be complex, have limitations and scope for error, but they nevertheless offer powerful capabilities for the prediction of potential impacts. They permit the testing of specific hypotheses by coupling simulations of real processes to field data, addressing the variation of one factor at a time and they also allow investigation of the integrated effects of various factors under certain assumptions. Therefore, in a scientific context, models must never be seen separately from the assumptions on which they are based. A good model, however, interpolates existing knowledge and can also extrapolate it, thus formulating predictions and stimulating their testing.

Their potential for use in monitoring strategies and for regulating or managing environmental impacts is less well recognized. Many hydrodynamic and benthic models have been proposed for use in aquaculture (Hargrave 1994; Nordvarg and Hakanson 2000), but very few are explicitly in use in regulation and monitoring and several countries do not apply them in the field of aquaculture at all, whereas others do make extensive indirect use of models. Their development and use in the assessment and prediction of impacts from nutrient release and hypernutrification, organic deposition to the sea bed, the dispersion of medicines and chemicals to the sea bed and water column has followed the growth of cage culture primarily. Some models are well developed, for example, in Northern Europe, USA and Canada.

The potential for model use can be seen in the following areas:

- as indicators (or warning signals) which might be used for adapting monitoring strategies and against which predetermined standards may be compared (Munday et al. 1992);
- as descriptors for well-understood physical processes (such as the settling of organic material around the fish cages);
- as tools for all sectors to achieve best practice within the process of aquaculture development and its regulation;
- as a cost-effective alternative to extensive field studies that may struggle to differentiate between anthropogenic impacts and the large variations that occur naturally;

- as a means of deriving fast predictions of potential impacts for different aquaculture scenarios;
- as contributions to the movement from reactive management to proactive management (Strain et al. 1995).

There still appears, however, to be a requirement for the politicians, planners, growers and many regulators, to fully commit to aquaculture and to learn to understand and describe the impacts (or their interaction) from aquaculture, where modelling could play a key role in developing a strategy for environmental management and sustainability. Despite the existing difficulties, there does seem scope to develop existing models and strategies, provided good and appropriate validation takes into account local socio-economic, political, management and environmental variations. Predictive modelling of complex interactions in an integrated way remains a matter for research in most of Europe (*ICES 1999*).

## Impacts in which modelling has a key role

Modelling of near-field (localized/site-specific) or far-field (regional/dispersed) impacts may be appropriate depending whether they derive from the production of particulate matter and dissolved effluents from cultured species, from any medicine or pesticide additions or from escaped fish themselves. The physical transport of effluents from a farm into the water column and sediments is driven by processes such as flushing (water exchange rates), sedimentation and resuspension parameters and characteristics.

### Nutrients [Nitrogen (N) and Phosphorus (P)]

Nutrients, with the potential to increase the risk of hypernutrification in areas with poor flushing characteristics, are released into the water column directly from caged fish and also from the sedimentary environment below the farm, from waste feed and interstitial waters (Aure and Stigebrandt 1990; Pitta et al. 1999; Davies 2000). These dissolved materials may have localized impacts but interest in the wider distribution of nutrients is still the subject of extensive research. Semi-intensive pond aquaculture, by contrast, produces relatively little nutrient pollution on a routine basis, and the nutrients discharged at harvest can be captured effectively using simple settling ponds (Costa-Pierce 1996).

Suspended shellfish culture is traditionally considered to result in a net consumption of nutrients from the ecosystem and there are proposals to apply suspended shellfish culture in coastal nutrient management in some Norwegian areas (Bodvin et al. 2000). Cultivation of shellfish has the potential of controlling phytoplankton blooms, through a series of feedback mechanisms that filter feeders exert in the ecosystem (Dame 1996; Prins et al. 1998). Nutrient release from extensive culture is now being reported and the studies reviewed by Prins and Smaal (1993) indicate a net release of ammonia, phosphate and silicate from bivalve beds.

### Organic impact

Organic impact from excess food and excretory matter that is deposited on the sea bed from fish culture and biodeposition around shellfish farms is localized and usually creates a site-specific 'impact footprint' below or around the installation. The impact can be extreme (Tenore et al. 1982), causing reduced dissolved oxygen levels, fish stress, afaunal sediments, outgassing, the production of fungal *Beggiatoa* mats and also impacting on normal sediment chemistry and microflora. Such gross impacts though, are usually confined to within 50 m of the fish cages (Hansen et al. 1991; Holmer 1991; Henderson and Ross 1995; Karakassis et al. 1999). 'Displaced' impacts are not uncommon in moderately dynamic waters where organic wastes do not deposit immediately around the premises. In some areas, wind-driven dispersion may be extremely significant. This, coupled with possible resuspension of sediments will determine the dispersion and mitigation of any organic impact. The recovery of sites from intense organic pollution from fish cages or suspended shellfish culture, can take many years and there is evidence that only an unstable equilibrium of benthic infauna and sediment chemistry is established in the sediments and that this can very easily be disrupted (Nickell et al. 1998; Karakassis et al. 1999).

### Medicines

The use of antibiotics and antiparasitics in European marine fish farming varies widely among countries. Although the former has declined in northern Europe in recent years, the demand for sea-lice treatments has increased. Several have now been developed and are marketed as both bath and in-feed treatments. Specific formulations can be used legally in several countries. However, the scientific investigation of the fate and pathways of these substances in the marine environment is still poorly understood and requires research.

### Trace metals

Although the usage of metalliferous antifoulants at cage farms in Norway and Scotland appears to be declining due to regulation and market forces, elevated levels of copper and zinc (List II EC Dangerous Substances), from nets and land-based net washers, have been recorded in Scotland (Miller 1998) and Norway (NIVA 1994). There is evidence also from France, that fish feed yields elevated metals in sediments (Kempf et al. 1997).

## Modelling process issues

It is important to ensure sound science using the best available information and that modelling outcomes are 'fit for purpose'. The process requires a statement of objective; a justification of the model; a technical description of the model; clearly defined source data; an understanding of the limitations of data collection, calibration and validation against independent data sets; a sensitivity analysis; quality assurance and control including auditability; accountability and reporting of summary outputs (these terms are defined in Henderson et al. 2001).

The specific needs of growers and producers, regulatory mechanisms and operational factors, require a different focus in the modelling arena. Models can be extremely simple, descriptive or mathematical and range in complexity from the simplest box model (item A plus item B in = item C out) to the modelling of highly complex integrated ecological systems and the conditions that drive them. Increasing complexity can lead to reduced reliability, particularly in situations where individual processes are poorly described and/or weakly understood. In order that the modelling process retains credibility with the industry, the public and non-government organizations, the modeller, the grower or the regulator needs a tool to be appropriate and fit for purpose; for example, to take account of whether near-field (localized) or far-field (regional) issues are being addressed and also to determine whether existing models require any or further validation for environmental or biotic factors.

This should enable regulators to efficiently and fairly issue licences with environmental confidence and provide farmers with reliable answers to different production scenarios. There is a need for openness by the regulator to promote confidence in the regulatory mechanism. Models need to be user friendly, fast and cost effective. The Working Group reporting on Environmental Interactions of Mariculture (ICES 1999) have recommended that there should be a review of the availability, to the scientific community, of mathematical models concerning the environmental interactions of mariculture. In the final scenario, users may be faced with a choice between using different models for different purposes, or accepting inaccuracies and limitations. It is also recognized that output from a model is as good as the data being entered and that the best available data should therefore be used where possible.

Limitations in modelling might result in false predictions. Consequently, there are risks in applying a modelling approach to any decision-making strategy, where complex environmental processes are oversimplified on the one hand, but a regulator or planner requires a uniform, understandable management tool on the other.

#### Special considerations for model development and validation

The physical, biotic, technical and socio-economic environment in which the models are to be applied will affect the modelling process and its application by the user. Examples of necessary environmental considerations include geographically varying hydrodynamic regimes (including macro/micro tidal conditions, still or dynamic regimes), local topography (bays, open waters), temperature, nutrient fluxes, poor nutrient status and phosphorus-limited systems. Furthermore, differences in species cultured, growing/culture technique, site management and feed type will vary spatially and temporally. The culture techniques and impact studies relate mostly to salmon (*Salmo salar*), rainbow trout (*Oncorhyncus mykiss*) and mussels (*Mytilus edulis*) for organic, nutrient, medicine and chemical impacts in, for example, Canada, USA, Norway, Scotland and Ireland, particularly in fjords and embayments. The models in use are consequently validated and calibrated for conditions and species in those locations and have limited application elsewhere in southern Europe, without the relevant regional validation and calibration. A number of these environmental and other factors can be illustrated from the Mediterranean sea (Karakassis et al. 1999).

### Overview of the current use of models and a country review

From the data available it was evident that relatively few models were used explicitly in regulation but many countries were using the tools, indirectly, to aid in the decision-making process. Their development has generally taken place in northern Europe, Canada and the USA where, to date, finfish farming has become a prime industry and the impacts of the industry are widely contested.

In addition to models which have been developed for use in regulating and monitoring aquaculture, there are many used in research and other domains that, although unlikely to be immediately suited to managing impacts from aquaculture, do cover the main processes, and could be developed for aquaculture. ICES (1999, 2000) has been responsible for collating and reporting much of the current viewpoint on modelling in relation to salmon aquaculture.

At present models are being used in relation to:

- *Regulation, licensing and environmental impact assessment (EIA)*
  - *setting holding capacity*: in setting biomass/production of fish farms on a site-specific basis, to achieve sustainability;
  - *licensing of medicines*: in the prediction of safe usage according to risk assessment and environmental quality standards (EQSs);
  - *EIA assessments for site applications*: in the prediction of organic waste footprints and faunal impacts, dissolved oxygen depletion and nutrient enhancement.
- *Monitoring*
  - *environmental monitoring*: in the prediction of environmental risk (spatial or temporal) for targeting monitoring effort and the validation/testing of model predictions against derived EQSs for environmental protection.
- *Site management*: growth and production model predictions
  - *exploitation capacity*: production optimization for shellfish, fish growth predictions.

A summary of the status and examples of the use of models used in the regulation of nutrient, organic and medicine impacts, follows, together with some examples from across Europe (north to south). Some examples of the software and its application are presented in Annex 1.

#### Modelling of nutrient impacts – summary

Although there is little definitive evidence of heavy nutrient enhancement in the marine environment from aquaculture, modelling can potentially address the issue at both the local and the regional scale and currently is targeted at the wider scale. Inputs of dissolved N and P excretion by fish are usually combined with the flushing characteristics of the water body although it is recognized that dietary composition and digestibility are important variables. Impact models to assess dispersion of soluble (and particulate wastes) have required the use of hydrodynamic models, such as two-dimensional hydrographic models (Dudley et al. 2000) which can be expensive. Day-to-day management of site-specific issues requires quick configuration and application and the modelling of mean environmental conditions can allow this.

In some countries an approach which ranks modelled enhancement of nutrients can assess, in simple terms, the risk to the aquatic environment. EQSs have been set in a number of countries against which to predict levels from the model. Modelling has seldom been used for the multi-farm/user scenario which will be a key to regulation in the future. Good two- and three-dimensional hydrodynamic models such as those are used in Ireland, will aid this process.

- Norway: some regional authorities in Norway intend to use, as part of a box model, a simple water quality classification based on dissolved oxygen levels, for the regulation of salmon farm size and location.
- Finland: a Baltic approach to modelling environmental impacts from nutrients and organic waste was published in 1991 (Makinen 1991) but has never been adopted by the regulators.

- Sweden: models for potential use by the regulator are under development (Nordvarg and Hakanson 2000). Baltic models, based on mass balance equations for phosphorus (the limiting nutrient in the Baltic) that predict the increase in surface water total phosphorus due to fish farm emissions, have been developed as a tool to assist in coastal planning, in order to identify areas that are potentially sensitive to fish farm development. In addition, a model predicting the variability in oxygen concentration and consumption, thus assessing risk areas in the Baltic coastal area, has been developed by Carlsson et al. (1998).
- Denmark: in Denmark, modelling *per se* is not used for the regulation of mariculture although there is an overall limit to the release of nutrients and organic matter to Danish waters based on HELCOM studies for the Baltic.
- The Netherlands: an ecosystem model developed for the Oosterschelde ecosystem has been used to simulate the impact of nutrient input reduction by shellfish, to the Oosterschelde estuary.
- Scotland: simple box models (e.g. MDL CNSNT 1) are in use to predict cage farm impacts on nutrient levels (Gillibrand and Turrell 1997b). The flushing times of the majority of lochs in Scotland are published (Edwards and Sharples 1986) and they can be used to develop a modelling strategy (nutrient enhancement model) where water body flushing rates can drive risk assessment, i.e. rapidly flushed systems may not be at risk. The regulators and consultees use these during the application EIA and licensing process.
- Ireland: in Ireland two- and three-dimensional hydrodynamic models (DIVAST and TRIVAST) are in use to study plumes of nutrients from cages. Recent developments have included a link between a hydrographic data module and nutrients module, to predict nutrients enhancement. Such a model is equally applicable and is used to predict inputs of medicines. This approach is used by the fish farm industry (their consultants) in Ireland for environmental impact statements (EIS), as part of the application process. They have also been used in a multi-farm scenario. No environmental quality (EQ) targets have been developed by the regulator.
- France: in France, models are recommended, as a regulatory tool within the EIS, to obtain an exploitation permit. The models most frequently used are mathematical models describing the hydrodynamics in a tidal environment (i.e. areas of the European continental shelf). They can be attached to a fish waste production model and are used to estimate soluble and settleable loadings, along with their concentration and deposition. These models are run by the fish farm applicants. A linear model to predict dissolved organic nitrogen from a recirculating system by sea bass (*Dicentrarchus labrax*) is in use and for open systems, a modification of the metabolic model of Stigebrandt (1995) has been developed. Carrying capacity models that predict the optimal standing shellfish biomass to be raised in a given basin or bay have been used in two cases, to give advice to the regulations authorities (Bacher et al. 1998).
- Portugal: there are no models in use for regulation or EIA but a trophic capacity modelling approach is being used to simulate bivalve growth, and determine the carrying capacity of cultured areas as a function of sediment quality, water circulation, bathymetry and human impact.

**Modelling of organic impacts – summary**

The deposition of organic-rich waste on the sea bed is targeted by modelling on a localized, for example, 200 m scale. The potential footprint of the organic waste and its dispersion characteristics/intensity, is modelled using particle tracking or deposition models. These utilize the settling characteristics of feed and faeces and the dispersal characteristics of the water body, based upon the fundamental approach initially described by Gowen et al. (1989). Alternatives are to use simple flushing models to calculate loading levels (Silvert 1992) and methods described by Hevia et al. (1996). Recent work has also led to models such as DEPOMOD (Cromey et al. 2000) being developed and extended to include benthic biological impacts and also resuspension.

ICES (1999) reports that the main recent developments are the recognition: (i) that fish faeces may not closely resemble coherent particles; and (ii) of the importance of resuspension of bottom sediments in some locations and the consequential redistribution of sedimented waste.

The models in use can be used during the EIA and consultation process to predict impacted areas in a water body or on the sea bed and these, combined with EQS for biological or carbon deposition, are now used to regulate impacts.

- Norway: impact models have been developed to study the spreading of faeces and particulates under marine cage farms. These are completed but not in routine use at the time of writing. The models are part of the Modelling/Ongrowing Fish Farms/Monitoring (MOM) system (Hansen et al. 1997). The models compute the release of particulate waste, settlement on the sea bed and nutrient release. They can also be used to assess oxygen consumption in cages.
- Scotland: for cage fish farms in Scotland, OPENSED (Gillibrand and Turrell 1997a), a modification of Gowen's carbon deposition model, is in use by the Scottish Executive Rural Affairs Department for EIA assessment. The model is a particle-tracking model which simulates advection and diffusion in two dimensions using a random walk technique. DEPOMOD (Cromey et al. 2000) has recently been developed to predict deposition of organic and medicinal waste and to predict benthic biological impacts, in terms of an 'infaunal trophic index' (Codling and Ashley 1992). The Scottish Environment Protection Agency (SEPA) is committed to adopting the model as a further aid to establishing appropriate biomass limits and impact zones at fish farm sites. (DEPOMOD is already used in the regulation of in-feed medicines). The model comprises modules covering the hydrodynamic regime, dispersion, settlement, resuspension, medicine decay, fish growth, the degradation of carbon and biological community changes. Currently, licensing maximum site biomass of finfish is used to indirectly manage seabed impacts. Alongside the use of DEPOMOD, hydrographic data (mean current speed and direction, current residuals plus period of still water) and benthic infaunal data are used in a simple relationship 'decision guidance model' by SEPA (1998). Biological quality criteria have been set against which to monitor the sustainability of the site. Development work is underway to determine the appropriateness of these models for waters in Shetland and Orkney Islands, where organic impacts may be mitigated by weather-driven events.
- Ireland: the model DIVAST predicts sediment deposition below cages, although the model has limitations in terms of

settlement rates of faeces and feed. Benthic quality criteria are being developed.
- Spain: an ecosystem modelling approach (not being covered in detail within the scope of this paper), where the impact on the benthic fauna was included has been comprehensively reported (Tenore et al. 1982) and applied in calculating mass balances and for providing an insight into the carrying capacity of the suspended mussel culture in the Spanish rias. An academic group are currently working with the aquaculture industry and Spanish government on benthic impact assessment and modelling of fish farm debris (Ruiz et al. 1999).
- Portugal: ecological models for extensive aquaculture in Portugal have linked high aquaculture activity with oxygen depletion, with fish production being dependent on natural food availability and environmental conditions (Gamito 1997). No regulation takes place using these models.

#### Modelling of medicines impacts – summary

The use of antibiotics in many European countries has been extensive but is declining. However, novel bath treatments or in-feed preparations for sea lice has required models (identified below in appropriate paragraphs) to address the spread of dissolved substances or particulates to which the medicines are attached. The models can be used during the EIA and consultation processes to predict impacted areas, in a water body or on the sea bed and combined with EQSs for specific treatments, are now used to regulate the substances.
- Scotland: in order to regulate the use of sea-lice treatment chemicals it is necessary to predict the dispersion following treatment. Models of medicines dispersion are already available for semi-enclosed Scottish sea lochs (Turrell 1990; Davies et al. 1991; Gillibrand and Turrell 1997a, b). As the environmental standards set for medicinal residues in Scottish waters and sediments after treatment are, in some cases, below the analytical detection limit, a modelling approach has been adopted for regulation. Predictive models are therefore used to set target values for residues, depending on the current speed, the dispersion coefficient of the waters at the site and the behaviour/concentration of the medicine at treatment. The approach is used by the regulator, to set a permitted quantity that the farm may use. DEPOMOD (Cromey et al. 2000) has been modified for in-feed lice treatments to take account of differing half lives of the medicines, their persistence in sediments, resuspension along the sea bed and also to take account of differing digestive loss through the fish itself. The regulator has further developed the decision-making process by setting environmental target criteria/EQSs, to permit a predicted safe level of use, on a site-by-site basis and to determine retreatment levels.
- Ireland: the model DIVAST predicts soluble and particulate medicine transport from fish cages.
- Italy: most aquaculture in Italy is land based and specific aquaculture models for regulation are rare. The fugacity models (EQC – Environmental Toxicology and Chemistry) of Di-Guardo et al. (1994) relate to impacts from chemicals. Another model (SOILFUG) also has the potential for use in impact assessment from aquaculture chemicals. There is work in progress to study the environmental impact of antibiotics drugs from aquaculture and also on water contamination by human and veterinary drugs (D. Calamari 2000, personal comm.).

### Overview of future developments

Future developments are likely to be developed to predict impacts in a more integrated way and to take account of multi-user and multiple quality objectives. In this manner, impacts may be likely to be studied, more specifically, at either a local or a regional level. For continuity however, developments are recorded below by impact rather than by scale.

#### Finfish farming

**Nutrient impacts.** Cage farms are being encouraged into more open waters, consequently the risk of hypernutrification may be diminishing. Structured research and major models however, are still needed to investigate this issue. Detailed models will be required to take account of 'whole' sea or regional systems from the regulatory point of view and should include diffuse sources, such as land run off or forestry and farming as a source of nitrogen and phosphorus. Nutrient budgets will need to be considered. Although tools exists to take into account overlapping farm 'footprints' or where a number of sites are located in a single system, they are not widely applied. The development in Ireland of MODESTIS (Hartnett 2000, personal comm.), a two-dimensional multiparameter model, may provide a step towards supplying regulators with a water quality tool to assess impacts from multiple cage farms within one water body.

The main areas of development required in 'large' multifarm models is likely to be resource driven and include the further enhancement of existing methods that take into account the proportion of water which leaves the inlet on one tide and returns on the next. This will require the acquisition of better data sets to give a better knowledge of environmental ranges. There is also a recognition of the importance in some areas of bottom currents, induced by wind/waves, in the resuspension and redistribution of material from the sea bed (ICES 1999). The main flushing/water exchange mechanisms differ between areas. In some cases, tidal flushing is dominant, in others freshwater inputs have strong effects on the current pattern. In areas, such as the Mediterranean Sea and Shetland Island Voes, water movements can be dominated by episodic events in response to winds. The modelling of episodic or exceptional events which could greatly influence the environment, is very complex. Additionally, areas where highly changeable environmental conditions prevail will also prove a challenge.

**Organic impacts.** A resume of approaches to modelling organic impacts of fish farms up to 1994 is given by Hargrave (1994) and extensive work in evaluating models is presented by Silvert (1994). Progress has been made in linking the physics of particulate waste deposition with the response of the benthic community. Studies of the changes of benthic communities over time, in response to benthic enrichment from fish farms, have been reported (Sowles et al. 1994). It has also been shown that a predictive model could be developed for sites exposed to constant carbon loading, which can take several years to reach maximum impact. A predictive model based on the balance of benthic oxygen supply and demand has also been developed in Maine for use in siting decisions (Findlay and Whatling 1997).

Wildish et al. (1999) have explored the identification of useful, economical and cost-effective proxy indices [redox potential (Eh) and sulphide content] to quantify benthic impacts in the Bay of Fundy. A similar approach using pH and redox is included in the MOM process. Quantitative and qualitative sediment quality criteria (sulphide, redox, trace metals) have been set recently, by SEPA (1998), alongside benthic infaunal criteria, to determine monitoring and regulation action levels.

Benthic scavenging on excess pellets or faeces falling through the water column can reduce the actual deposition of these materials on the sea bed and is recorded in Scotland, Israel and French Mediterranean sites. The risk of waste in-feed medicines pellets being consumed by scavenging fish and spread through the food chain has also been highlighted recently. Such processes are recognized as important, but reliable (realistic) modelling is not yet possible. A combination of modelling with empirical field data would probably be required and is recommended (ICES 1999).

There is continued development of DEPOMOD to incorporate a module to assess dissolved oxygen availability to the benthos and effects of dissolved oxygen stress and it is intended that DEPOMOD be freely available to researchers and regulators within the EU (Black 2000, personal comm.). SEPA is developing a strategy for using DEPOMOD to set site-specific biomass.

The impact of structures is under serious discussion (W. Silvert, personal comm.) and routine modelling may take place at some future date. These structures include cages, rafts and ropes, all of which produce drag or friction, that may impact on the local hydrodynamics of the growing area, indirectly affecting the local settling and resuspension characteristics of the site. In Cherbourg bay the current velocity was found to increase under the cage nets, decreasing the deposition of material immediately under the cages (Merceron et al. 1997). Currently regulators do not take this impact into routine consideration.

**Medicines.** In developing risk assessments for the use of sea-lice medicines, EQSs have been developed to protect the marine environment and non-target species. As some of these EQSs in waters and sediments are below the detectable limit analytically, a predictive modelling approach has been developed by the regulators to determine safe levels for use in the marine environment in those countries where they are controlled. Strict treatment regimes for the medicines are key to a modelling approach and although a site-specific approach is relevant, the whole water body lice treatment strategies being adopted by the industry will require a wide-field approach. In addition, the fate and pathway of the active ingredient or its breakdown products, is often not well understood and issues of chemical decay, retreatment times and resuspension of sediments for in-feed medicines are critical areas for impact prediction modelling. Advective and diffusion models are relevant to predicting effects of chemicals and work is progressing in Canada.

There are plans to add a hydrodynamic model to DEPOMOD in addition to the sea-lice treatments component (K. Black 2000, personal comm.). The latter will aim at predicting concentrations in sea water for soluble treatments and in sediment and biota, for in-feed treatments.

**Trace metals and biocides.** The Health and Safety Executive in the UK, is becoming increasingly concerned about the use of antifoulants in relation to aquaculture and some interest is being shown by this body, in developing a modelling approach to impact and risk assessment.

#### Shellfish farming

**Nutrient impacts.** Shellfish-related models are not currently applied to regulatory objectives but originate from eutrophication-related studies, addressing nutrient cycling in ecosystems. The main references to benthic–pelagic model studies are reviewed in Heip et al. (1995) and Herman et al. (1999). Studies in San Francisco Bay (Officer et al. 1982) and more recently by Lucas et al. (1999) model the role of shellfish or benthic filter feeders.

The 'production' and 'carrying capacity' models that have been developed for shellfish culture were brought together at the TROPHEE workshop in Plymouth, UK in 1996 (Bayne and Warwick 1998). Production models looked at the growth and development of bivalves under different conditions. Scholten and Smaal (1999) presented a model which aimed to simulate growth and reproduction of individual mussels, which was to be used as a management tool in eutrophication and carrying capacity studies. Models by Frechette and Bacher (1998) found that mussel growth could be modelled as a function of stocking density and the results provided much of the information usually required for managing cultured populations.

A mussel production model, MUSMOD (Campbell and Newell 1998) was developed to seed bottom culture lease sites in Maine to their optimal carrying capacity. This model predicted mussel production from a number of physical and biological variables. Carrying capacity models which operate at local scale and are applied in site selection or at ecosystem scale, consider growth of shellfish as a function of ecosystem characteristics such as primary production, standing stock of bivalve filter feeders and interaction with other competitors such as zooplankton.

Another experience in relation to nutrient impacts, is the culture of shellfish in nutrient-poor environments, as is now carried out in Norway. Recent studies have shown that nutrient addition to an oligotrophic Norwegian fjord enhanced scallop and mussel growth (Reitan 2000). In this framework model development also takes place.

**Seabed modelling.** Research on modelling the benthic impact of mussel farming, primarily by adapting the fish farm impact model DEPOMOD has recently been conducted in Scotland and Ireland (Chamberlain et al. 1999). Initial results suggest that the predicted rate and extent of deposition of waste could be linked to the observed impact on sediment and benthic fauna. Further data on the settling rate of faeces and pseudofaeces and on the temporal variation on seston levels is required. Similar research is presently being conducted in Canada with the added objective of incorporating a benthic primary production component. Research has also been conducted in France to determine the impact of biodeposits from oyster table systems in the region of Marenne-Orlean and suspension line culture in the Etang de Thau region (Bacher et al. 1998).

A similar modelling approach is currently being developed for suspended mussel culture in Saldanha Bay (South Africa). The impact of biodeposits on the benthic community was described by Stenton-Dozey et al. (2000) and empirical data are now integrated in a STELLA-based model, according to the ECOPATH approach described by Christensen and Pauly (1993). Simulations were made of the impact of mussel rafts on community composition (Stenton-Dozey and Shannon 2000).

#### Integration

A more integrated treatment and management approach is now underway, which will require models to take account of whole loch systems and any treatment strategies adopted by the industry. With the development of infectious salmon anaemia in Scotland in 1998/99 a more integrated approach to sea-lice treatments will require rapid development of models. General models are now being integrated with models of ecosystem processes, particularly pelagic processes and nutrient regeneration from sediment (e.g. the ERSEM model). Ecosystem models are under development which are multiparameter, multifunctional models directed at studying whole loch systems over an annual cycle (W. Gurney 1999, personal comm.). MODESTIS (Hartnett 2000, personal comm.) is an example used in Ireland for predicting total water quality. Predictions of conditions likely to promote toxic algal blooms also requires to be addressed. An ecological model of the Sado estuary in Portugal is being developed, to integrate the estuarine nutrient dynamics and analyse the relative importance of industrial, domestic and fish farm effluents, the productivity and the plankton–benthos interactions. Integration within the framework of coastal zone management considers the development of decision support systems. Although still in an experimental phase, reference can be made to such an approach for the Wadden Sea (results are accessible through internet http://www.waddense.nl.) Other models which are evolving in coastal zone management, studying the interactions of aquaculture with other water users, include a fuzzy logic expert system called SIMCOAST (McGlade and Price 1993; McGlade 1997).

### Key conclusions

- The explicit use of models in planning regulation and impact management is very limited but it appears that considerable implicit use does occur in the regulation process.
- Models appear to be best developed where aquaculture is well established as a growth industry, for example, Norway, Scotland, Canada and USA.
- Effective modelling of impacts from aquaculture is taking place primarily in northern Europe.
- Current models are considered to be limited in scope but do cover the main hydrodynamic and particle processes.
- The integration of modelling into regulation and monitoring programmes is not accepted Europe-wide.
- Many models exist that are related to non-aquaculture impacts. Some of these are freely available. Others are under development.
- Key areas of modelling uncertainty surround: settling velocities/faecal quality and feed type, dispersion coefficients, resuspension parameters and characteristics, whole water body/multi-farm impacts, holding capacity, nutrient fluxes, ecosystem effects.
- Considerable expertise exists in European Institutes and scientific organizations.
- Different approaches have been developed in different countries in relation to determining holding or carrying capacity, planning and regulation.
- Keys to the future developments include accessibility, definition of EQSs, training and support for users, resourcing, and structured research.

### Recommendations

#### General

- The use of a modelling approach in aquaculture planning, regulation and monitoring should be encouraged.
- Modelling should be regarded as an objective tool to optimize resource exploitation, to support activities in many sectors of aquaculture including growth prediction, impact management (e.g. organic waste, medicines, antifoulants, genetics), coastal zone management and planning and resource management. Regulation should not rely on modelling alone.
- Flexibility in the decision-making process involving model output must be maintained.
- There requires to be an enabling environment for the use of models across Europe. This will require commitment from governments and regulators, an investment in training, free and easy access to non-commercial users of existing models, technical support and training programmes.
- Modelling should be used as part of the monitoring strategy. Where possible modelling can predict directional or temporal impact thus allowing a targeting of sampling resource and also areas at 'risk' from impacts.
- Modelling results should be taken into account when regulatory guidelines are developed. EQSs should be set locally or regionally to allow models to be developed for setting exploitation capacity.

#### Modelling processes

- Models require to be scaled appropriately.
- Model validation must be an integral part of the modelling process taking account of any special physical, biotic or zoogeographical variation. Best available data should be used.
- Credibility of regulation using models necessitates good validation and fit of observed against predicted values. Due regard must be taken of model limitations and assumptions. The accuracy of prediction required will depend on the purpose of the model. ICES (1995) recommends the use of confidence limits around predictions.
- Models require to be fit for purpose, fast, user-friendly, as simple as possible, cost effective and transparent as possible. Outputs should be easily interpreted, e.g. graphical or contoured outputs.

#### Availability and development

- Existing hydrodynamic water quality models currently constructed should be made available to support aquaculture development and validated, taking account of special environmental or socio-economic considerations. Information/data exchange should also be encouraged and the delivery of models to the client might be enhanced by expert systems (decision support systems).
- There is a major data constraint on the application of models in supporting aquaculture development and its regulation which in turn is determined by inadequate funding or research.
- Existing impact models and their performance, e.g. DEPOMOD, MOM and OPENSED should be evaluated and be made available for non-commercial use (e.g. universities, growers or regulators) then validated for other locations taking into account local special considerations.

- The development across Europe of site-specific and 'regional' models to set holding capacity for aquaculture enterprise, are required as a matter of urgency.
- The development across Europe of models to address whole water body impacts from solutes (nutrients and medicines) and also multi-farm inputs, are required as a matter of urgency.

**Acknowledgements**

Thanks are due to staff at the Scottish Environment Protection Agency; Dunstaffnage Marine Laboratory, Oban; the Scottish Marine Laboratory, Aberdeen; Anders Stigebrandt, University of Goteborg, Sweden; Michael Hartnett, University of Galway, Ireland and all MARAQUA partners who contributed to the preparation and review of this paper.

**References**

Aure, J.; Stigebrandt, A., 1989: A Consequence Analysis of the Environmental Impact on 30 Fjords in More og Romsdal. Report No. FO8803. Bergen, Norway: Directorate of Fisheries, Institute of Marine Research.

Aure, J.; Stigebrandt, A., 1990: Quantitative estimates of eutrophication effects on fjords of fish farming. Aquaculture **90,** 135–156.

Bacher, C.; Duarte, P.; Ferreira, J. G.; Heral, M.; Raillard, O., 1998: Assessment and comparison of the Marennes-Oléron Bay (France) and Carlingford Lough (Ireland) carrying capacity with ecosystem model. Aquat. Ecol. **31,** 379–394.

Bayne, B. L.; Warwick, R. M., (Eds), 1998: Feeding and growth of bivalves: observations and models. TROPHEE workshop in Plymouth, UK in 1996. J. Exp. Mar. Biol. Ecol. **219,** 269 pp.

Bodvin, T.; Haamer, J.; Dahl, E.; Anderson, P., 2000: Recycling nutrients from the sea to land with mussel farming: a sustainable solution of the eutrophication problem? Hydrobiologia, in press.

Campbell, D. E.; Newell, C. R., 1998: MUSMOD ©, a production model for bottom culture of the blue mussel, *Mytilus edulis* L. J. Exp. Mar. Biol. Ecol. **219,** 171–203.

Carlsson, L.; Persson, J.; Hakanson, L., 1998: A management model to predict seasonal variability in oxygen concentration and oxygen consumption in thermally stratified coastal waters. Ecol. Modelling **119,** 117–134.

Chamberlain, J.; Fernandes, T. F.; Read, P.; Nickell, T. D.; Davies, I. M., 1999: Modelling the benthic impact of mussel (*Mytilus edulis* L.) farming. In: Environmental Effects of Mariculture 1999 (Abstracts). Eds: D. J. Wildish and M. Heral. New Brunswick, Canada: ICES. 63 pp.

Christensen, V.; Pauly, D., 1993: Trophic Models of Aquatic Ecosystems. ICLARM Proc. 26. Ecopath.

Codling, I. D.; Ashley, S. J., 1992: Development of a Biotic Index for the Assessment of Pollution Status of Marine Benthic Communities. Report No. NR 3102/2404/ 4280. Medmenham, England: Water Research Centre. 90 pp.

Costa-Pierce, B. A., 1996: Environmental impacts of nutrients from aquaculture: towards the evolution of sustainable aquaculture systems. In: Aquaculture and Water Resource Management. Eds: D. J. Baird, M. C. M. Beveridge, L. A. Kelly and J. F. Muir. Oxford, England: Blackwell Science. pp. 81–113.

Cromey, C. J.; Black, K. D.; Edwards, A.; Jack, I. A., 1998: Modelling the deposition and biological effects of organic carbon from marine sewage discharges. Estuarine Coastal Shelf Sci. **47,** 295–308.

Cromey, C. J.; Nickell, T. D.; Black, K. D., 2000: DEPOMOD – A Model for Predicting the Effects of Solids Deposition from Mariculture to the Benthos. Oban, Scotland: Dunstaffnage Marine Laboratory.

Dame, R. F., 1996: Ecology of Marine Bivalves: an Ecosystem Approach. Boca Raton, USA: CRC Press. 254 pp.

Davies, I. M., 2000: Waste Production by Farmed Atlantic Salmon (*Salmo salar*) in Scotland. ICES ASC 2000, CM 2000/O 01. Aberdeen, Scotland: ICES. 6 pp.

Davies, I. M.; Turrell, W. R.; Wells, D. E., 1991: The Observation and Simulation of the Dispersion of DDVP in Loch Ailort – August 1990. Scottish Fisheries Working Paper, 15/91. Aberdeen, Scotland: SOAEFD Marine Laboratory. 6 pp.

Di-Guardo, A.; Calamari, D.; Zanin, G.; Consalter, A.; Mackay, D., 1994: A fugacity model of pesticide runoff to surface water: development and validation. Chemosphere **28,** 511–531.

Dudley, R. W.; Panchang, V. G.; Newell, C. R., 2000: Application of a comprehensive modelling strategy for the management of net pen aquaculture transport. Aquaculture **187,** 319–349.

Edwards, A.; Sharples, F., 1986: Scottish Sea Lochs: a Catalogue. Edinburgh, Scotland: Nature Conservancy Council. 110 pp.

Ervik, A.; Kupka Hansen, P.; Aure, J.; Stigebrandt, A.; Johannessen, P.; Jahnsen, T., 1997: Regulating the local environmental impact of intensive marine fish farming. I. The concept of the MOM system (Modelling-Ongrowing fish farms-Monitoring). Aquaculture **158,** 85–94.

Findlay, R. H.; Whatling, L., 1997: Prediction of benthic impact for salmon net pens based on the balance of benthic oxygen supply and demand. Mar. Ecol. Prog. Ser. **155,** 147–157.

Frechette, M.; Bacher, C., 1998: A modelling study of optimal stocking density of mussel populations kept in experimental tanks. J. Exp. Mar. Biol. Ecol. **219,** 241–255.

Gamito, S., 1997: Sustainable management of a coastal lagoonal system (Ria Formosa, Portugal). An ecological model for extensive aquaculture. Int. J. Salt Lake Res. **6,** 145–173.

Gowen, R. J.; Bradbury, N. B.; Brown, J. R., 1989: The use of simple models in assessing two of the interactions between fish farming and the marine environment. In: Aquaculture – a Biotechnology in Progress. Eds: N. de Pauw, E. Jaspers, H. Ackefors and N. Wilkins. Bredene, Belgium: European Aquaculture Society. 1071–1080.

Gillibrand, P. A.; Turrell, W. R., 1997a: Simulating the Dispersion and Settling of Particulate Material and Associated Substances from Salmon Farms. Report No. 3/97. Aberdeen, Scotland: Fish Res. Services Marine Laboratory. 20 pp.

Gillibrand, P. A.; Turrell, W. R., 1997b: The use of simple models in the regulation of the impact of fish farms on water quality in Scottish sea lochs. Aquaculture **159,** 33–46.

Gillibrand, P. A.; Turrell, W. R., 1999: A Management Model to Predict the Dispersion of Soluble Pesticides from Marine Fish Farms. FRS ML Report 2/99. Aberdeen, Scotland: SERAD, FRS. 31 pp.

Hansen, P. K.; Ervik, A.; Aure, J.; Johannessen, P.; Jahnsen, T.; Stigebrandt, A.; Schanning, M., 1997: MOM Concept and Revised edition of Monitoring Programme 1997. Fisken Og Havet Nr 7. Bergen, Norway: Havforskningsinstituttet. 51 pp.

Hansen, P. K.; Pittman, K.; Ervik, A., 1991: Organic waste from marine fish farms – effects on the sea bed. In: Marine Aquaculture and Environment. Ed.: T. Makinen. Copenhagen, Denmark: Nordic Council of Ministers. pp. 105–119.

Hargrave, B. T., 1994: Modelling benthic impacts of organic enrichment from marine aquaculture. In: Canadian Technical Report of Fisheries and Aquatic Sciences 1949. Ed.: B. T. Hargrave. Nova Scotia, Canada: Canadian Fisheries and Aquatic Sciences. 175 pp.

Heip, C. H. R.; Goosen. N. K.; Herman, P. M. J.; Kromkamp, J.; Middelburg, J. J.; Soetaert, K., 1995: Production and consumption of biological particles in temperate tidal estuaries. Oceanogr. Mar. Biol. Ann. Rev. **33,** 1–150.

Henderson, A. R.; Ross, D. J., 1995: Use of macrobenthic infaunal communities in the monitoring and control of the impact of marine cage fish farming. Aquaculture Res. **26,** 659–678.

Henderson, A. R.; Gamito, S.; Karakassis, I.; Pedersen, P. B.; Smaal, A. C., 2001: The use of hydrodynamic and benthic models for managing environmental impacts. In: MARAQUA – The Monitoring and Regulation of Marine Aquaculture in Europe. Eds: P. A. Read, T. F. Fernandes and K. L. Miller. Brussels, Belgium: European Commission.

Herman, P. M. J.; Middelburg, J. J.; van de Koppel, J.; Heip, C. H. R., 1999: Ecology of estuarine benthos. Adv. Ecol. Res. **29,** 195–240.

Hevia, M.; Rosenthal, H.; Gowen, R. J., 1996: Modelling benthic deposition under fish cages. J. Appl. Ichthyol. **12,** 71–74.

Holmer, M., 1991: Impact of aquaculture on surrounding sediments: generation of organic rich sediments. In: Aquaculture and the Environment. Eds: N. de Pauw and J. Joyce. Special Publication 16. Ghent, Belgium: European Aquaculture Society. pp. 155–175.

ICES, 1995: ICES Working Group, Modelling Environmental Interactions of Mariculture. Dartmouth, Nova Scotia, Canada: ICES. 11 pp.

ICES, 1999: ICES Working Group on Environmental Effects of Mariculture 1999: Abstracts. St Andrews, New Brunswick, Canada: ICES. 63 pp.

ICES, 2000: ICES Working Group on Environmental Interactions of Mariculture. Aberdeen, Scotland: ICES. 10 pp.

Karakassis, I.; Hatziyanni, E.; Tsapakis, M.; Plaiti, W., 1999: Benthic recovery following cessation of fish farming: a series of successes and catastrophes. Mar. Ecol. Prog. Ser. **184**, 205–218.

Kempf, M.; Cadour, G.; Jeanneret, H.; Méar, H.; Miramand, P.; Merceron, M., 1997: Impact de la salmoniculture marine sur l'environnement en rade de Cherbourg (1993–95): II. Etude biosédimentaire. Rapport no. DEL/97–05/BREST. Brest, France: IFREMER. 71 pp.

Lucas, L. V.; Koseff, J. R.; Cloern, J. E.; Monismith, S. G.; Thompson, J. K., 1999: Processes governing phytoplankton blooms in estuaries: I the local production-loss balance. MEPS **187**, 1–15.

Makinen, T., (Ed.), 1991: Marine Aquaculture and Environment. Nord: 22. Copenhagen, Denmark: Nordic Council of Ministers. 126 pp.

McGlade, J. M., 1997: Sustainable Use and Management of Resources: Role of Governance in Theoretical Ecology, 3rd edn. Edinburgh, Scotland: Blackwell Science.

McGlade, J. M.; Price, A. R. D., 1993: Multidisciplinary modelling: an overview and practical implications for the governance of the Gulf region. Mar. Pollut. Bull. **27**, 361–377.

Merceron, M.; Bentley, D.; Le-Grand, J.; Lamort-Datin, L.; Kempf, M., 1997: Impact of Salmonid Sea Farming on the Environment in the Rade of Cherbourg: I – Water and Pelagos (1993–95). Plouzane, France: IFREMER Cent. Brest. 54 pp.

Miller, B. S., 1998: An Assessment of Sediment Copper and Zinc Concentrations at Marine Caged Fish Farms in SEPA West region. SEPA Internal Report. East Kilbride, Scotland: SEPA. 75 pp.

Munday, B.; Eleftheriou, A.; Kentouri, M.; Divanach, P., 1992: The Interactions of Aquaculture and the Environment: a Bibliographical Review. Brussels, Belgium: Commission of the European Communities, DG Fisheries. 325 pp.

Nickell, T. D.; Black, K. D.; Provost, P. G.; Davies, I. M.; Pearson, T. H., 1998: The Recovery of the Sea-bed after the Cessation of Fish Farming: Benthos and Biogeochemistry. ICES, CM 1998/V 1. New Brunswick, Canada: ICES. 20 pp.

NIVA, 1994: Distribution of Sediment Properties in Coastal Areas Adjacent to Fish Farms and Environmental Evaluation of Five Locations Surveys in October 1993. Projects O-93205, O-93206. Oslo, Norway: Norwegian Institute for Water Research. 33 pp.

Nordvarg, L.; Hakanson, L., 2000: Predicting the environmental response of fish farming in coastal areas of the Aland archipelago using management models for coastal water planning. In press.

Officer, C. B.; Smayda, T. J.; Mann, R., 1982: Benthic filter feeding: a natural eutrophication control. Mar. Ecol. Prog. Ser. **9**, 203–210.

Panchang, V.; Cheng, G.; Newell, C., 1997: Modelling hydrodynamics and aquaculture waste transport in coastal Maine. Estuaries **20**, 14–41.

Pitta, P.; Karakassis, I.; Tsapakis, M.; Zivanovic, S., 1999: Natural vs mariculture induced variability in nutrients in the Eastern Mediterranean. Hydrobiologia **391**, 181–194.

Prins, T. C.; Smaal, A. C., 1993: The role of the blue mussel *Mytilus edulis* in the cycling of nutrients in the Oosterschelde estuary (The Netherlands). Hydrobiologia **282/283**, 413–429.

Prins, T. C.; Smaal, A. C.; Dame, R. F., 1998: A review of feedbacks between bivalve grazing and ecosystem processes. Aquat. Ecol. **31**, 349–359.

Reitan, K. I., 2000: Response of shellfish culture to enhanced nutrient supply and experimental fertilisation. In: Proceedings of First MARICULT Conference, June 2000, Trondheim, Norway. Eds:. In press.

Ruiz, J. M.; Belmonte, A.; Uriarte, A.; Giménez, F., 1999: Metodología de evaluation del impacto ambiental producido por los cultivos marinos en jaulas flotantes. Canarias: Congreso Nacional de Acuicultura. 12 pp.

Scholten, H.; Smaal, A. C., 1999: The ecophysiological response of mussels (*Mytilus edulis*) in mesocosms to a range of inorganic nutrient loads: simulations with the model EMMY. Aquat. Ecol. **33**, 83–100.

SEPA, 1998: A Manual of Regulation and Monitoring for Cage Fish Farming in Scotland. Stirling, Scotland: Scottish Environment Protection Agency. 120 pp.

Silvert, W., 1992: Assessing environmental impacts of finfish aquaculture in marine waters. Aquaculture **107**, 67–79.

Silvert, W., 1994: Modelling benthic deposition and impacts of organic matter loading. In: Canadian Technical Report of Fisheries and Aquatic Sciences 1949. Ed.: B. T. Hargrave. Nova Scotia, Canada: Canadian Fisheries and Aquatic Sciences. pp. 1–18.

Sowles, J. W.; Churchill, L.; Silvert, W., 1994: The effect of benthic carbon loading on the degradation of bottom conditions under farm sites. In: Canadian Technical Report of Fisheries and Aquatic Sciences 1949. Ed.: B. T. Hargrave. Nova Scotia, Canada: Canadian Fisheries and Aquatic Sciences. pp. 31–46.

Stenton-Dozey, J.; Probyn, T.; Busby, A., 2000: Impact of mussel raft-culture (*Mytilus galloprovincialis*) on benthic macrofauna, *in situ* oxygen uptake and nutrient fluxes in Saldanha Bay, South Africa. Can. J. Fish Aquat. Sci.

Stenton-Dozey, J.; Shannon, L., 2000: Impact of mariculture on ecosystems: an ecopath approach to assess the effect of mussel culture on trophic interactions. In: Proceedings of First MARICULT Conference, June 2000, Trondheim, Norway. Eds:. Town: Publisher. In press.

Stigebrandt, A., 1995: A Model for the Dispersion of Organic Waste from a Fish Farm. Fisken og Havet 26, Appendix 1. Bergen, Norway: Havforskningsinstituttet. 27 pp. (in Norwegian).

Stigebrandt, A., 1999: Turnover of Energy and Matter by Fish – a General Model with Application to Salmon. Fisken og Havet 5. Bergen, Norway: Havforskningsinstituttet. 26 pp.

Stigebrandt, A.; Aure, J., 1995: Model for Critical Organic Loads Beneath Fish Farms (MOM). Fisken og Havet 26. Bergen, Norway: Havforskningsinstituttet. 60 pp. (in Norwegian).

Strain, P. M.; Wildish, D. J.; Yeats, P. A., 1995: The application of simple models of nutrient loading and oxygen-demand to the management of a marine tidal inlet. Mar. Pollut. Bull. **30**, 253–261.

Tenore, K. R.; Boyer, L. F.; Cal, R. M.; Corall, J.; Garcia-Fernandez, C.; Gonzalez, N.; Gonzalez-Gurriaran, E.; Hanson, R. B.; Iglesias, J.; Krom, M.; Lopez-Jamar, E.; McClain, J.; Pamatmat, M. M.; Perez, A.; Rhoads, D. C.; de Santiago, G.; Tietjen, J.; Westrich, J.; Windom, H. L., 1982: Coastal upwelling in the Rias Bajas, NW Spain: contrasting the benthic regimes of the Rias de Arosa and de Muros. J. Mar. Res. **40**, 701–772.

Turrell, W., 1990: Simulation of Advection and Diffusion of Released Treatments in Scottish Sea Lochs. Scottish Fisheries Working Paper, 16/90. Aberdeen, Scotland: SOAEFD Marine Laboratory. 25 pp.

Wildish, D. J.; Akahgi, H. M.; Hamilton, N.; Hargrave, B. T., 1999: A recommended method for monitoring sediments to detect organic enrichment from mariculture in the Bay of Fundy. In: Canadian Technical Report of Fisheries and Aquatic Sciences 2286. New Brunswick, Canada: Canadian Fisheries and Aquatic Sciences.

**Authors' addresses:** A. Henderson (for correspondence), Scottish Environment Protection Agency, Redwood Crescent., East Kilbride, Glasgow G76, Scotland. E-mail: anne.henderson@sepa.org.uk; S. Gamito, UCTRA, University of Algarve, Faro, Portugal; I. Karakassis, Institute of Marine Biology of Crete, PO Box 2214, Heraklion 71003, Greece; P. Pederson, Ministry of Food, Agriculture and Fisheries, Institute of Fisheries Research, The North Sea Centre, PO Box 101, DK-9850 Hirsthals, Denmark; A. Smaal, Rivo DLO, Centre for Shellfish Research, PO Box 77, 4400 AB Yerseke, The Netherlands

Edited by H. Rosenthal, Kiel (Editor-in-Chief)

Vol. 17 (4), 145–206 August 2001

## Special Issue

# MARAQUA
# The Derivation of Scientific Guidelines for Best Environmental Practice for the Monitoring and Regulation of Marine Aquaculture in Europe

**Proceedings of the 3rd Workshop held at Napier University, Edinburgh, Scotland, 28–31 August 2000**

**Guest Editors:** P. A. Read, T. F. Fernandes and K. L. Miller

**European Union FAIR Programme, PL98-4300 (1999–2000)**

*b* **An online version is available via www.blackwell.de/synergy**

http://www.blackwell.de