Ecosystem based management: models and mariculture

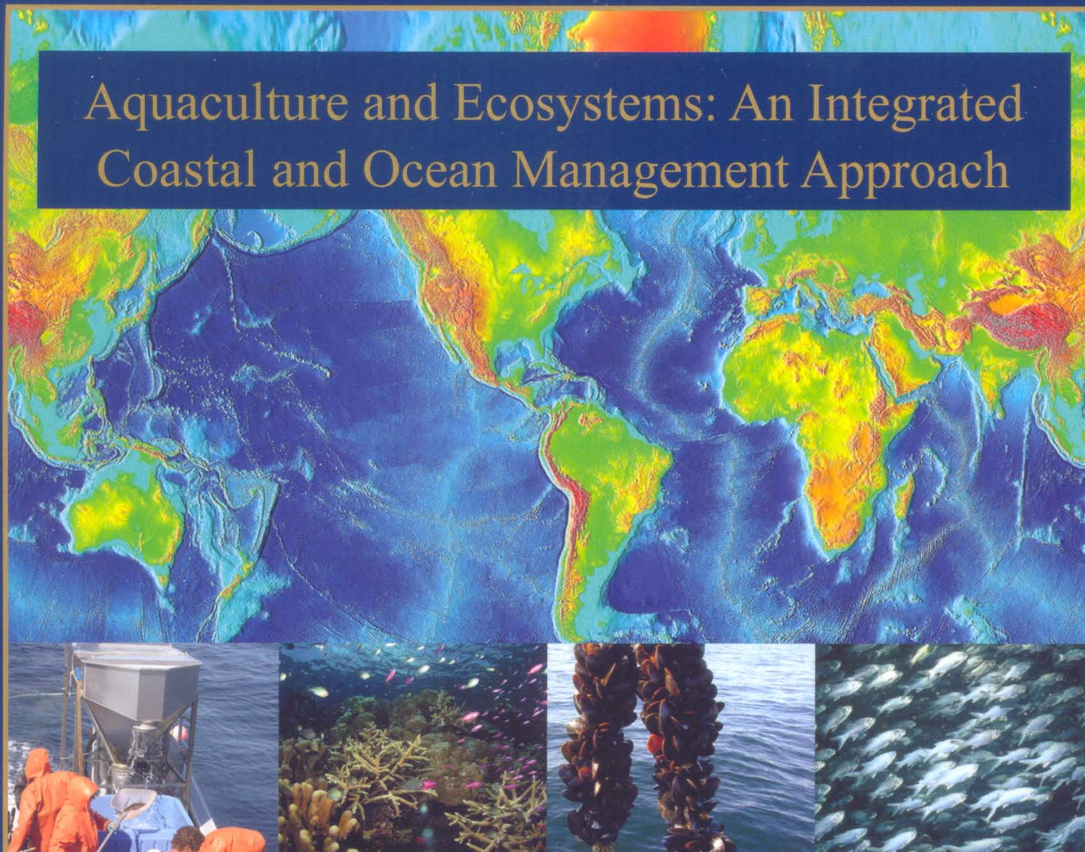
Alejandro H. Buschmann
Universidad de Los Lagos

Thierry Chopin
University of New Brunswick

I. K. Chung
Pusan National University

Richard Langan
University of New Hampshire

Aquaculture and Ecosystems: An Integrated Coastal and Ocean Management Approach



Edited by

James P. McVey, Cheng-Sheng Lee and Patricia J. O'Bryen

Published by

WORLD AQUACULTURE SOCIETY

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

Oceanic Institute
An Affiliate of Hawai`i Pacific University

10 ECOSYSTEM BASED MANAGEMENT: MODELS AND MARICULTURE

Introduction

Conceptual and numerical models are essential tools in managing and protecting coastal ecosystems. Models may be used in economic, social, and ecosystem simulations for many purposes, including aquaculture design, siting, and operation; ecosystem management and risk assessment; and integration of sustainable mariculture into restoration and management of coastal ecosystems.

At the Ecosystem workshop, particular emphasis was placed on the application of ecosystem models to understand the influence of fed and extractive forms of mariculture and their interactions with the natural environment. Participants recognized the limitations of existing models, i.e., they are typically more useful to assist in the prediction of the possible directions and types of interactions rather than predicting absolute or precise quantitative changes.

Waste products from fed mariculture systems may have a range of effects from nutrient enrichment of the water column and benthos to neutral effects where assimilation by the natural biota is equal to the rate of input. There may even be positive effects, such as food web enhancement of diversity and abundance of benthic organisms in more ideal situations where fish mariculture is sized appropriately and strong currents disperse organic and inorganic wastes.

In less than ideal physical conditions or where nutrient sensitivity is an issue, mariculture of species receiving a food ration (e.g., fish or shrimp) may be coupled with shellfish and/or seaweed capable of extracting nutrients from consumption of enhanced phytoplankton stocks or directly through nutrient removal. This is termed "integrated mariculture" in the literature, or more precisely, "integrated multi-trophic aquaculture," and may be designed to eliminate adverse effects of fed finfish culture. Organic matter and nutrient additions by cultured fish do not have to be perfectly balanced with nutrient removal in space and time as long as the biological communities can assimilate the nutrient loads without adversely changing the composition and character of these communities.

Extractive shellfish and seaweed mariculture offers significant benefits to coastal ecosystems through reduction of excess nutrient loading known as coastal eutrophication.

Contributors: Rensel, J.E.J, A.H. Buschmann, T. Chopin, I.K. Chung, J. Grant, C.E. Helsley, D.A. Kiefer, R. Langan, R.I.E. Newell, M. Rawson, J.W. Sowles, J.P. McVey, and C. Yarish
In J.P. McVey, C.-S. Lee, and P.J. O'Bryen, editors. Aquaculture and Ecosystems: An Integrated Coastal and Ocean Management Approach. The World Aquaculture Society, Baton Rouge, Louisiana, United States.

Worldwide, many coastal seas are suffering from adverse effects of eutrophication which can include oxygen depletion, changes in species composition and in some case harmful algae events. Although not typically defined as such, integrated mariculture could also include directing finfish facilities to areas where companion, extractive crops are not needed due to certain local characteristics.

Some areas with strong tidal current that prevent permanent solids deposition and concurrently that are not nutrient sensitive would not benefit from integrated mariculture to mitigate the effects of fed finfish culture. Algae and nutrients do not limit primary production in high current velocity, deep water, and nutrient insensitive areas (e.g., Cobscook Bay in Northern Maine, USA, and main channels of Puget Sound and the Strait of Juan de Fuca in Washington State that experience light limitation of phytoplankton). Solid wastes from fish mariculture in these areas are periodically resuspended until they are incorporated aerobically into the food web. In general, other areas may be desirable for mariculture if its scale remains within the carrying capacity of the water body so that byproducts enhance, rather than degrade, existing marine resources. In the context of ecosystem-based mariculture, coastal resource managers may achieve protection of sensitive areas while addressing the larger need for food production and coastal economies. Worldwide, only limited coastal areas qualify as physically and chemically optimal for fish mariculture when all siting requirements are considered. In tropical or subtropical areas, especially those near shore, nutrient enrichment may have negative effects, and integrated mariculture would be beneficial in some cases. Initial observations of offshore cages in tropical areas indicate that there may be a food web response to mariculture discharge resulting in increased numbers of invertebrates and fish near the cages. These effects can be positive as long as the enrichment does not flow onto coral reefs and it is aerobically assimilated into the biological community in the surrounding area.

Although mariculture is often believed to have undesirable impacts on coastal ecosystems, the modeling session participants recognized that some forms of mariculture can become part of a solution to coastal problems caused by non-mariculture activities such as point and non-point source nutrient inputs, habitat destruction, and over-fishing. There was consensus among the international participants that models should describe levels and types of effects from mariculture. After some discussion, however, it was agreed that determining "what is acceptable" in terms of end point impacts or benefits is a separate informed political decision made on the basis of each country's local customs, policies, and laws.

Purpose and Use of Models

The purpose and use of models are highly variable and serve the mariculture industry, government planners, scientists, as well as the general public. Some examples of uses include:

- Siting mariculture facilities

- Issuing permits for mariculture operations
- Making decisions and planning the economics of mariculture
- Optimizing mariculture operations
- Assisting in the technical planning and management of mariculture operations
- Identifying opportunities to integrate mariculture activities into solving coastal problems
- Hindcasting "baseline" conditions
- Identifying gaps in knowledge of mariculture activities
- Characterizing and quantifying ecological processes and pathways
- Estimating the effects of human perturbation on the ecosystem
- Educating and communicating with the public

Characteristics and Types of Models

Characteristics of Models

Model characteristics vary widely depending on their purpose, origin, and user. For example, some coastal managers are generally interested in models that are simple, easily understood, completed in a timely fashion with minimal resources, and which have the ability to convey educational messages to the public. On the other hand, researchers engaged in answering complex questions of ecological pathways and fluxes are interested in models that can accommodate more detailed and quantitative biological, chemical, and physical processes. Mariculturists may be interested in the results of modeling by both coastal managers and scientists as well as running their own models on costs and benefit analyses for various husbandry, siting, and operational practices.

There is recognition that complexity is not necessarily a virtue in modeling. Between the extremes of simplicity and complexity, the practicality and "power" of models must be balanced. For example, models with high precision, accuracy, and thoroughness generally need extensive, high-resolution data to allow complete parameterization. Furthermore, such models require advanced computer systems not typically available to coastal managers or mariculturists. Advancing understanding of coastal ecosystem dynamics, complex food webs, and processes, however, will require the use of the more advanced and complex models that rely on extensive databases and computations. As a greater understanding of an ecosystem is developed, complex models may often be simplified as the lesser important variables and components are quantified.

Desirable characteristics of some models include:

- Ease of use and understandability
- Validity that can be established through incorporation of measurable Environmental Quality Objectives
- Ability to assess effects at a scale appropriate to management needs
- Provision to address near and far field effects
- Assumptions, boundaries, and compartments are well defined
- Ability to interface with other models

Several general categories of models exist that can be helpful to the management of Ecosystem Based Mariculture. These include:

- Physical (e.g., hydrodynamic, circulation, wave energy, and plume trajectories)
- Chemical (e.g., sediment diagenesis and chemical transformations)
- Biological (physiological, growth, food web, bioturbation[1], and energetics)
- Resource economics-based (e.g., intrinsic value of shellfish and seaweed for bioremediation services to manage eutrophication)
- Coupled or integrated models – (e.g., integration of any or all the above, typically physicochemical and biological).

The following general comments are made regarding origins, applications, and limitations of models, drawn from a discussion paper the authors prepared prior to the meeting:

- Many estuarine and coastal ocean models were designed for other purposes, e.g., municipal and industrial waste discharge plume characterization or circulation studies.
- No fully functional models yet exist that completely integrate water column and benthic effects of mariculture into a single package[2] or interlinked modules that accurately reproduce benthic-water column coupling.
- Benthic impact models for finfish mariculture are developing but they are still evolving

[1] Disturbance of sediment layers by biological activity.

[2] A GIS model known as AquaModel performs these simulations but it is currently being validated and tuned.

to more fully account for various processes including resuspension, saltation (leaping of particles across an uneven surface), bedload[3] transport, and assimilation or bioturbation by differing types of benthic or other fauna and flora. Much remains to be learned about rate constants of aquaculture waste feed and fish feces assimilation in the food web in terms of carbon flux in differing habitats and ecoregions using differing culture techniques, species, and types of feed.

- Several suitable hydrodynamic models are available for water column physical description, but few adequately integrate or link to biological components and processes.

- No existing single model will likely serve all purposes. There is a need for different models with a variety of levels of hydrodynamic sophistication, tuning ability, physiological bases, and eventually, linkage to economic models.

- Different but complementary models may be selected and linked together. For example, water column and benthic models may be linked, but the technical aspects of linking such models so that the various modeled components, such as nutrients or oxygen, are accurately transferred between modeled domains is not a trivial process.

- Lack of species-specific physiological information prevents accurate description of waste products or assimilation (bio-mitigation) processes needed to develop suitable biological models. Some species are well described (salmonids and mussels), but many others are not (various marine fish, some shellfish, crustaceans, and seaweeds).

- Validation of models is often not conducted but is essential. Site-specific calibration is also necessary. Similarly, assumptions and limitation are not always explicit in documentation but they should be.

- Models are not acceptable substitutions for compliance monitoring in North America and are never used for enforcement actions. Predictive impact models are required in some countries for permitting (e.g., large scale finfish mariculture in Scotland).

- Models are currently being developed in the aquaculture therapeutant approval process by the U.S. Food and Drug Administration and the U.S. Environmental Protection Agency.

- Complex models may not be practical for use by public sector managers and regulators or by individual mariculturists or companies. For broad, regional modeling, however, there is a need for complexity to adequately simulate variable and complex hydrographic, physicochemical, and biological conditions and to understand and define boundary conditions of these processes.

[3] Sediment moving on or near the streambed of seabed and frequently in contact with it.

- Pragmatic realism is a necessary aspect of modeling, because "All models are wrong. Some models are useful" (DiToro 2001). Not all models are intended to exactly simulate reality. Some models only seek to give insight into key processes, bottlenecks (constrictions) in natural systems, and missing or erroneous components of modeling needing attention.

Types of Models

Following are some examples of models ranging from simple to complex, including several that previously have been used for mariculture applications.

Simple One-Box Models

Box models are one of the most common types of models used by coastal managers, particularly for semi-enclosed bays or waterways. Single box models can be developed using readily available inputs such as surface areas from nautical or topographic charts and volume estimates from published literature or user-performed estimates. Mass balance models are a form of box model that account for principle inputs and outputs of selected properties such as river or seawater, dissolved oxygen, macronutrients (dissolved, particulate, and organic fractions of N and phosphorus, P), particulate carbon, and various types of pollutant measures. Most importantly, these simple and inexpensive models produce results quickly for coastal decision-makers and are easily understood by the general public.

Mass balance nutrient models that seek to quantify inputs and losses of nutrients are among the most useful of these simple models, by providing coastal managers an approximate estimate of the potential effect of nutrient addition or extraction. Very often, however, these types of models fail to take into consideration the assimilative capacity of the surrounding ecosystem, and they equate primary production to phytoplankton production, ignoring the significant nutrient scrubbing function of aquatic macrophytes (submerged aquatic vegetation and seaweeds). Depending on the results, managers may quickly approve or deny a project, or decide that further modeling and/or monitoring is required.

Examples of simple one-box and mass balance models include:

- Tidal prism and salt balance models to estimate flushing rates that are widely used
- Mass balance models that estimate net loss and/or uptake of a constituent by calculating differences between known inputs and removals. At the workshop, John Sowles presented a mass balance model for N in the Gulf of Maine. Other models of this type include those by Gowen et al. (1992) and Sowles and Churchill (2004).
- Combined simple flushing models coupled to biogeochemical/ecological models based on previous studies in a "broad-brush" generic review and comparison of estuaries, as used in Australia (CSIRO 2001). A recent example is that of Grant et al. (2005) in which biodeposition impacts are assessed for mussel culture in eastern Canada.

Index Models

Index models provide a ranking of impacts relative to other water bodies, operations, or technologies. These employ one-box models or empirically derived relationships that have been quantified through measurement, correlation, and other means. Although their absolute accuracy may be variable, these indices are useful to managers and mariculturists responsible for deciding management options including the best location among several options for a certain proposed activity or the degree of impact of existing practices, including aquaculture. Some examples include:

- Index of Suitable Location and Embayment Degree Model used in Japan (Abo and Yokoyama 2005).
- Nitrogen loading model and oxygen depletion indices for Puget Sound, Washington, USA bays and subareas (SAIC 1986; Rensel Associates and PTI 1991; Albertson et al. 2002)
- Benthic oxygen uptake, carbon assimilation, and sulfide content models (several)
- Scottish management indices (e.g., Gillibrand et al. 2002)

Multiple Box Models

Multiple box models are an iteration between one-box models and complex hydrodynamic models with extensive grid representation. In general, the hydrodynamics are collapsed into spatially integrated inter-box exchange coefficients which are used directly in the box model, and are thus decoupled from the hydrodynamic grid. Ecosystem structure may be as detailed as more spatially explicit models, but complexity and computation time are reduced, making them excellent exploratory tools. They have generally been used to examine density-dependent and food-limited growth in bivalve culture, and/or benthic and nutrient impacts of shellfish farming. A recent example is:

- Model of dispersion in Tracadie Bay, Prince Edward Island, Canada where impacts of mussel culture were modeled (Dowd 2005; Grant et al. 2005)

Benthic Impact, Particle Tracking Models

This class of generally well-advanced models is used to predict carbon accumulation on the sea bottom, effects on the benthos, and related topics. Newer benthic models may include a resuspension component to estimate re-distribution of benthic materials by water currents above a critical resuspension threshold. Resuspension components are useful in macrotidal or strong ocean current regimes but they are not necessarily needed in slower, depositional areas. Examples include:

- DEPOMOD (Cromey et al. 2002a, 2002b) is a widely used, personal computer platform, carbon-based benthic model developed for temperate water finfish mariculture with several submodels dealing with consolidation, resuspension, carbon degradation, and bioturbation. A similar model, developed as part of the MERAMED project in 2005 (www.akvaplan.niva.no/meramed/download), has been adapted for use in the Mediterranean Sea, where wild fish actively feed on waste feed from net pens.

- Perez et al. (2002) report a carbon-based model with Global Information Systems (GIS) underpinnings and no resuspension component, validated for depositional sites.

- The Aquaculture Waste Transport Simulator model, AWATS (Panchang et al. 1997; Dudley et al 2000) is a vertically averaged, two-dimensional flow model with particle-tracking waste transport processes. It is among the first models to consider resuspension to simulate the resulting transport of wastes.

Two- or Three-Dimensional Hydrodynamic Models Linked with a Biological Model

These are complex conceptual and computational models that have the capacity to help scientists understand ecological processes, and they may be useful for broad geographic regions (far field) with complex bathymetry and hydrography. Sometimes referred to as coupled physical-biological models, they generated great interest among the workshop participants. These models have several disadvantages, including the requirement for extensive and often expensive database support, major computation power (will not run on personal computers), and require a long development time before output.

Examples of multidimensional models coupled with a biological or water quality model include:

- Finite Volume Community Ocean Model (FVCOM), with a Water Quality Analysis Simulation Program (WASP5) water quality module (Ambrose et al. 1993). This is a powerful and complex model. One example is by Chen et al. (1999).

- Princeton Ocean Model (Blumberg and Mellor 1980; 1987). This model has been widely used and redeveloped over time for ocean plume modeling.

Three-Dimensional Simplified Hydrodynamic Models within GIS Interface

Increasingly useful, especially in the public sector, are the moderate complex scale models that use three-dimensional (3-D) computations with simplified boundaries in a GIS context and a widely understood graphic user interface that operates on personal computers.

Hydrodynamic simulation is simplified to achieve the benefits of easy use by model users and managers. Because of their graphical format, these also have the distinct advantage of being an excellent teaching tool for audiences with diverse backgrounds.

As with several other types of models, 3-D GIS models require species-specific physiological information on metabolic rate, growth, nutrient ingestion, and excretion as well as hydrodynamic data or estimates of current velocity and disrection distribution.

An example presented at the workshop is AquaModel, a finfish mariculture model that runs within a GIS (Environmental Assessment System, EASy). This model concurrently simulates a farm's effects on water quality, including dissolved oxygen, dissolved nitrogen, and plankton dynamics, and it includes a benthic sedimentation and resuspension module. AquaModel traces the flow of carbon, nitrogen, and oxygen in the farm and ecosystem, it runs on a laptop and (data) can be shared in real time on the Internet (Rensel et al. in press).

Direction and Needs

Short Term Plan

The authors propose the development of a one-box index model (Fig. 1) to expedite investigation of ecosystem effects of mariculture activities for situations in which either

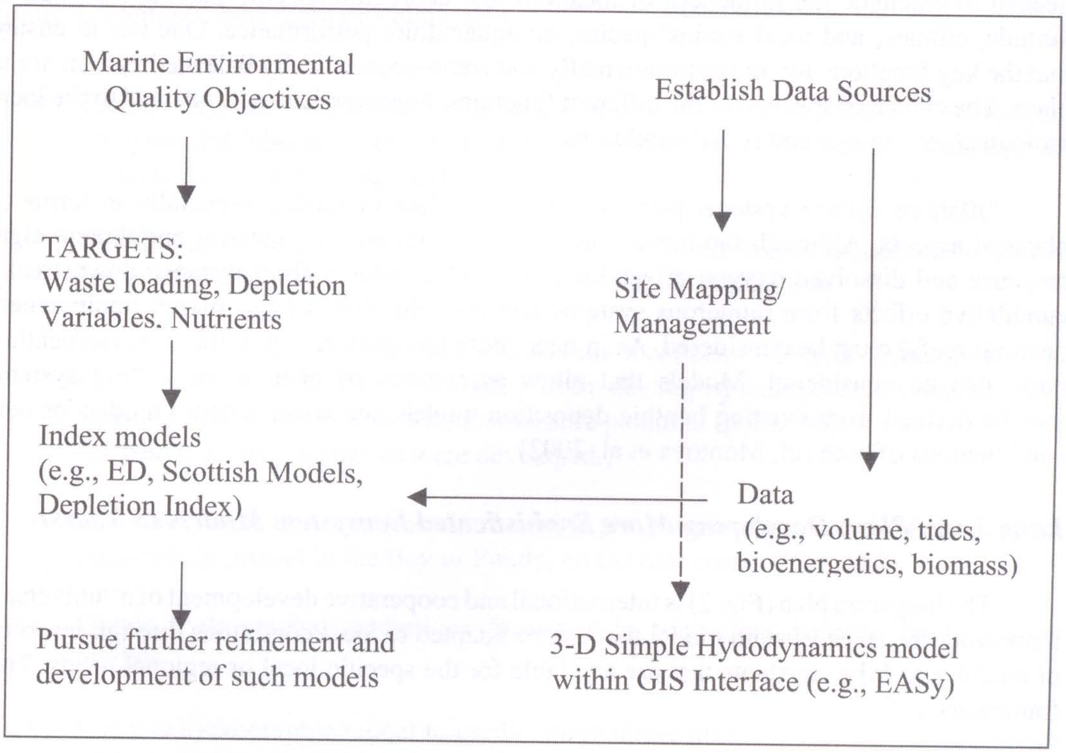


Figure 1. Proposed short-term modeling plan.

environmental data or the resources necessary for advanced modeling are limited. This model will be designed and implemented for several mutually agreed upon international locations, inshore and offshore, with at least one that currently has balanced, multi-species mariculture. This can likely be implemented within a 1- to 3-year time frame with little extra research.

A simple box model or 3-D simple hydrodynamic model within a GIS interface (as described above) can be developed to model the effect of cultured organisms on oxygen demand, N and P content, phytoplankton, opportunistic macroalgal growth, and particulate organic carbon deposition and transport. Such a model requires species-specific physiological information on metabolic and growth rates, nutrient ingestion/assimilation, and excretion, much of which is available for a few key species. Volume of water exchanged within an embayment can be estimated by an appropriate variation of the tidal prism method.

Concurrently, there is a need for better understanding of the temporal variability of effects from mariculture systems from varying feed regimes, physiological and biochemical processes of the cultured species and other factors. The roles and functions of integrated aquaculture practices for improved environmental, economic, and social acceptability should be analyzed within the broader perspective of integrated coastal management initiatives (Troell et al. 2003). Research into these advanced aquaculture technologies should be conducted at scales relevant to commercial implementation to be suitable for modeling, and should address the biology, engineering, operational protocol, and economics of the technology. Studies are needed to elucidate the influences of location- and ecoregion-specific parameters, such as latitude, climate, and local strains/species, on aquaculture performance. One has to ensure that the key functions for an environmentally and socio-economically balanced system are in place. The choice of species for the different functions, however, has to be adapted to the local biological, economic, and social conditions.

Offshore culture systems present a different class of model, especially in terms of physical aspects. Although the impact on the water column (i.e., nutrient enrichment-algal response and dissolved oxygen effects) may be undetectable a short distance downstream, cumulative effects from numerous systems and far-field effects (e.g., plume impingement on coral reefs) must be considered. As in near shore mariculture, local effect on the benthos must also be considered. Models that allow assessment of open water culture systems may be derived from existing benthic deposition models and water column models or new combinations of both (cf. Montoya et al. 2002).

Long Term Plan: Developing More Sophisticated Ecosystem Models (5 Years)

The long term plan (Fig. 2) is international and cooperative development of a "universal" framework for an ecosystem model that can be adapted to local conditions through insertion of modules and the constants that are available for the specific local or regional needs. This framework will:

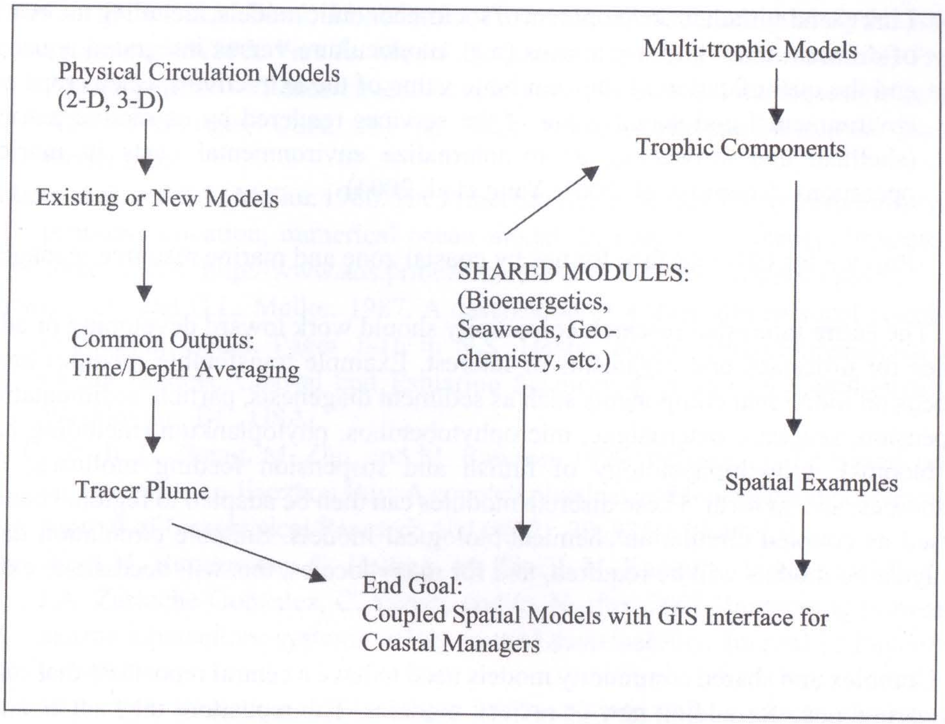


Figure 2. Proposed long-term modeling plan.

- Identify trophic interactions with some degree of certainty, allowing sensitivity analysis and laboratory (physiological submodels) or field studies (combining all submodels) for estimating model accuracy.

- Incorporate a minimal set of properties (e.g., functional components and shared modules) that may have quantifiable influence upon application.

- Use existing 2-dimensional, and in estuarine locations, 3-D hydrodynamic models of water circulation that have often been developed independently by physical oceanographers for regions with mariculture potential (preferably the same locations for which country scenarios were developed.)

- Use emerging integrated aquaculture models presently being developed (e.g., salmon/ mussel/kelp project in the Bay of Fundy, on the east coast of Canada).

- Obtain hydrographic predictions formatted in time steps suitable for biological models.

- Use this hydrographic model to predict mariculture plume movement under a range of tidal, riverine discharge to estuaries and oceanic current flows.

- Link to and stimulate development of socio-economic models, including the evaluation of different mariculture practices (e.g., monoculture versus integrated aquaculture) and the quantification of the economic value of the extractive species/crops and the environmental and social value of the services rendered by extractive mariculture (shellfish and seaweeds), as to internalize environmental costs in mariculture operations (Chopin et al. 2001; Yang et al. 2004)

- Provide for GIS interface for use by coastal zone and marine resource managers

The entire interested research community should work toward developing or adapting modules for processes and organisms of interest. Example transferable modules are those that focus on individual components such as sediment diagenesis, particle sedimentation and resuspension, seagrass, macroalgae, microphytobenthos, phytoplankton (including harmful algal blooms), growth/physiology of finfish and suspension feeding molluscs, fouling communities, and so forth. These discrete modules can then be adapted to regional conditions and used as coupled circulation/chemical/biological models. Suitable circulation data and hydrodynamic models will be required, and for many locales, this will necessitate extensive efforts.

Complex and shared community models need to have a central repository that can serve as a clearinghouse for adding new or revised modules. The repository may act as a contact point for groups wishing to implement managed mariculture ecosystem models. Accordingly there is a need to plan for long-term funding for such an entity.

This proposal includes development of a database of aquaculture and ecosystem constants and variables that will be needed for model development and use. Finally, it is emphasized that this approach does not displace or negate ongoing efforts in various countries that are presently using specific models. This proposal is meant as a further enhancement and catalyst. The authors believe this approach will compliment and encourage further development and validation for the models described above, which in turn will contribute significantly to the rational use of coastal and oceanic waters for sustainable mariculture.

Literature Cited

Abo, K. and H. Yokoyama. 2005. Assimilative capacity of fish farm environments as determined by benthic oxygen uptake rate: Studies using a numerical model. Proceedings of 33rd UJNR Aquaculture Panel Symposium. Nagasaki Japan.

Albertson, S.L., K. Erickson, J.A. Newton, G. Pelletier, R.A. Reynolds, and M. Roberts. 2002. South Puget Sound water quality phase 1. Washington State Department of Ecology Publication No. 02-03-021. Environmental Assessment Program, Department of Ecology, Olympia, Washington, USA. 224 pp. http://www.ecy.wa.gov/pubs/0203021.pdf.

Ambrose, R.B. Jr., T.A. Wool, J.L. Martin. 1993. The Water Quality Analysis Simulation Program, WASP5. Part A: Model Documentation. U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Athens, Georgia, USA. 251 pp. http://www.cee.odu.edu/mbin/wasp/dos/wasp5_model.pdf.

Blumberg, A.F. and G.L. Mellor. 1980. The Princeton Ocean Model (POM), a three dimensional primitive equation, numerical ocean model. Princeton University, Princeton, New Jersey, USA. http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/.

Blumberg, A.F. and G.L. Mellor. 1987. A description of a three-dimensional coastal ocean circulation model. Pages 1-16 in N.S. Heaps, editor. Three-Dimensional Coastal Ocean Models. Coastal and Estuarine Sciences 4. American Geophysical Union, Washington, DC, USA.

Chen, C., R. Ji, L. Zheng, M. Zhu, and M. Rawson. 1999. Influences of physical processes on ecosystem in Jiaozhou Bay: A coupled physical and biological model experiment. Journal of Geophysical Research 104 (C12): 29, 925-929, 949.

Chopin, T., A.H. Buschmann, C. Halling, M. Troell, N. Kautsky, A. Neori, G.P. Kraemer, J.A. Zertuche-Gonzalez, C. Yarish, and C. Neefus. 2001. Integrating seaweeds into marine aquaculture systems: a key toward sustainability. Journal of Phycology 37: 975-986.

Cromey, C.J., T.D. Nickell, and K.D. Black. 2002a. DEPOMOD – modeling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214: 211-239.

Cromey, C.J., T. D. Nickell, K.D. Black, P.G. Provost, and C.R. Griffiths. 2002b. Validation of fish farm waste resuspension model by use of a particulate tracer discharge from a point source in a coastal environment. Estuaries 25: 916-929.

CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2001. Simple Estuarine Response Model (SERM). National Land and Water Resources Audit. Marine and Atmospheric Research, CSIRO, Canberra, Australian Capital Territory, Australia. http://www.per.marine.csiro.au/serm/index.htm.

DiToro, D.M. 2001: Sediment Flux Modeling. Willey and Sons, New York, New York, USA. 624 pp.

Dowd, M. 2005. A bio-physical coastal ecosystem model for assessing environmental effects of marine bivalve aquaculture. Ecological Modelling 183: 323–346.

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

Gillibrand, P.A., M.J. Gubbins, C. Greathead, and I.M. Davies. 2002. Scottish locational guidelines for fish farming: predicted levels of nutrient enhancement and benthic impact. Scottish Fisheries Report 63/2002. Fisheries Research Services, Aberdeen, Scotland, UK. 52 pp.

Gowen, R.J., P. Tett, and K.J. Jones. 1992. Predicting marine eutrophication: the yield of chlorophyll from nitrogen in Scottish coastal waters. Marine Ecology Progress Series 85: 153-161.

Grant, J., P. Cranford, B. Hargrave, M. Carreau, B. Schofield, S. Armsworthy, V. Burdett-Counts, and D. Ibarra. 2005. A model of aquaculture biodeposition for multiple estuaries and field validation at mussel (*Mytilus edulis*) culture sites in Eastern Canada. Can. J. Fish. Aquat. Sci. 62: 1271–1285.

Montoya, R.A., A.L. Lawrence, W.E. Grant, and M. Velasco. 2002. Simulation of inorganic nitrogen dynamics and shrimp survival in an intensive shrimp culture system. Aquaculture Research 33: 81-94.

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

Perez, O.M, T.C. Telfer, M.C.M. Beveridge, and L.G. Ross. 2002. Geographical information systems (GIS) as a simple tool to aid modelling of particulate waste distribution at marine fish cage sites. Estuarine, Coastal and Shelf Science 54: 761–768.

Rensel Associates and PTI Environmental Services. 1991. Nutrients and phytoplankton in Puget Sound. U.S. Environmental Protection Agency Report 910/9-91-002. Environmental Protection Agency, Seattle, Washington, USA. 130 pp.

Rensel, J.E., D. Kiefer, J.R.M. Forster, D. Woodruff, and N.R. Evans. In press. Offshore finfish mariculture in the Strait of Juan de Fuca. 2004 U.S. Japan Cooperative Program in Natural Resources 33rd Annual Proceedings. Nagasaki, Japan. http://www.wfga.net/sjdf/reports/publication.pdf.

SAIC (Science Applications International Corporation) 1986. Recommended interim guidelines for the management of salmon net pen culture in Puget Sound. D. Weston for Washington State Departments of Ecology and Natural Resources. Publication 87-5. Department of Ecology, Olympia, Washington, USA. 48 pp.

Sowles, J. 2005. Assessing nitrogen carrying capacity for Blue Hill Bay, Maine - A management case history. In B.T. Hargrave, editor. The Handbook of Environmental Chemistry – Volume 5. Water Pollution: Environmental Effects of Marine Finfish Aquaculture. Springer-Verlag, Heidelberg, Germany.

Sowles, J. and L. Churchill. 2004. Predicted nutrient enrichment by salmon aquaculture and potential for effects in Cobscook Bay, Maine. Northeastern Naturalist 11(Special Issue 2): 87-100.

Troell, M., C. Halling, A. Neori, T. Chopin, A.H. Buschmann, N. Kautsky, and C. Yarish. 2003. Integrated mariculture: asking the right questions. Aquaculture 226: 69-90.

Yang, Y.F., C.H. Li, X.P. Nie, D.L. Tang and I.K. Chung. 2004. Development of mariculture and its impacts in Chinese coastal waters. Reviews in Fish Biology and Fisheries 14: 1-10.