XVII^th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

SUSTAINABLE ENVIRONMENTAL MANAGEMENT FOR TROPICAL FLOATING NET CAGE MARICULTURE, A MODELLING APPROACH

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CSBE101056 – Presented at Section VII: Information Systems Conference

ABSTRACT This paper presents a modeling approach for the development and management of floating net cage mariculture under sustainable operation. Suitable sites for marine fish cages are defined with respect to physical and water quality properties as well as coastal uses. Ranges of sustainable production are estimated with respect to environmental carrying capacity. The procedures involved are embedded into a decision support system (DSS) aiming to facilitate the planning process of sustainable marine finfish cage farming. Its application to a coastal site in Bali, Indonesia is demonstrated.

Keywords: Mariculture, Sustainable Environmental Management, Decision Support System

INTRODUCTION

Marine finfish aquaculture is a global industry which satisfies a rapidly increasing share of the demand for consumption fish (FAO 2006). Its sustainable development requires socio-economic and environmental considerations that ensure ongoing practice. They include identification of suitable sites and determination of the carrying capacity. There are various Decision Support Systems (DSS) already focussing on regions in Europe and North America to help identify suitable areas for several forms of mariculture producing finfish (Ross et al. 1993; Hargrave 2002). Only few apply to tropical coastal regions (Mayerle et al. 2006; Halide et al. 2009). Other studies use numerical models to simulate the dispersion of fish farm wastes in order to estimate their impact on the environment (Wu et al. 1999; Pérez Martinez et al. 2002; Doglioli et al. 2004). Some relate the effects of organic matter loading from fish farms to the carrying capacity (Cromey et al. 2002; Stigebrandt et al. 2004).

The present paper describes the application of numerical models and Geographic Information System (GIS) technology to assess the suitability of potential floating net cage sites and the assessment of the carrying capacity to facilitate environmental sustainable fish farming within a given domain. The DSS is exemplarily implemented for Pegametan Bay, situated at the northwest coast of Bali, Indonesia.

DSS METHODOLOGY

Suitability assessment

The assessment of spatial suitability for fish farming within a coastal area requires criteria for key physical and chemical parameters and coastal uses that allow a ranking with respect to suitable conditions for a predefined culture species. Subsequently, information is gathered and compared to these criteria as described in the following sections.

Hydrodynamic modelling

The Delft3D modelling suite is used to create a numerical hydrodynamic model. Model results provide information at high spatial and temporal resolution for the physical conditions that are used for the suitability assessment of floating net cage cultures such as current velocities, current directions, water level fluctuations and wave action within the area of interest.

Monitoring

Culturing fish in open water bodies, such as floating net cage cultures, require appropriate water quality to ensure adequate growth conditions and minimize the risk of disease and large-scale mortality. Adverse levels of temperature, salinity, dissolved oxygen as well as potentially toxic substances such as total ammonia nitrogen or high concentration of suspended matter may create critical rearing conditions. A supporting monitoring program provides valuable information of the water quality parameters that are related to the suitability for finfish cultures.

Geographic survey

A geographic survey is conducted to identify conflicting uses and adverse natural settings of the coastal zone. Apart from coastal management frameworks that might assign specific use to a coastal area, potential risks are identified. Appropriate distances should be kept from sea traffic lanes, harbours, urban and industrial agglomeration, rivers, land based culture activities, and coastal run off or coastal erosion areas to avoid adverse impacts on fish farming.

Spatial Suitability

The physical, chemical and geographic information as described above is collected in a GIS as spatial thematic grids. Reclassification of the thematic grids according to the suitability criteria is done assigning suitability scores, viz, 2 optimal, 1 allowable and 0 unsuited. Finally the reclassified grids are overlaid to determine the averaged suitability score for each grid cell with equal weight. Grid cells which score unsuitable for one of the parameters, result in an overall unsuitable score as demonstrated in Figure 1.

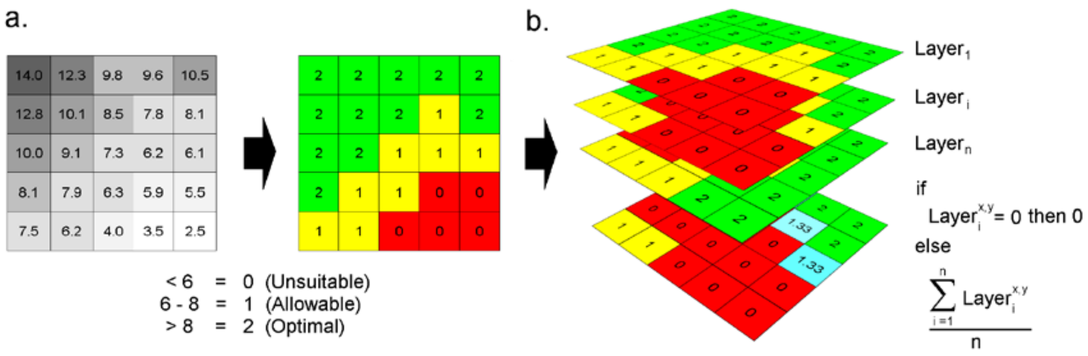

Figure 1: Scheme of the suitability assessment. Thematic grids are reclassified and scored as optimal (2), allowable (1) or unsuitable (0) (a). A final suitability score is computed for the reclassified grids of all available parameters (b).

Carrying capacity

Environmentally sustainable development for floating net cage culture is obtained when impact does not exceed the assimilative capacity of the surrounding environment. The possible degree of impact is strongly dependent on the rate of emission per unit of production and the production rate.

For the determination of the carrying capacity, fish farm emissions of particulate and dissolved nutrients are separately assessed. Emitted particulate organic matter may be measurable at ranges of 1.2 km however, adverse effects mostly occur in the near vicinity of the farms (Hargrave 2003). Dissolved compounds on the other hand, affect larger areas and supply essential nutrients for phytoplankton production that may exceeds removal rates (Hargrave 2003), and thus cause nutrient enrichment.

<u>Particulate matter</u>

The deposition rate of particulate organic matter occurring from faecal and wasted feed is influenced by the hydrodynamic of a site (Gowen et al. 1989). Assuming that the depth (D) and current velocity (V) govern the transport of a settling particle with a specific settling velocity, the dispersion and deposition rates of particulate organic matter is assumed to be correlated to the product DV adapted from a formulation of Yokoyama et al. (2004).

To estimate the carrying capacity of a site, the deposition rates of particulate organic carbon (POC) are modelled for different DV characteristics and production levels using a deposition model. Next, the hydrodynamic character DV is correlated to the POC deposition rates at different production levels.

Adverse effects of the benthic environment occur when POC deposition exceed 1-5g C/m²d (Angel et al. 1995; Findlay, 1997). These values are taken as range for the respective maximum deposition rates, preventing adverse effects to the benthos and hence may ensure sustainable fish farm operation.

<u>Dissolved nutrient flux.</u>

Dissolved nutrient loads released from mariculture may contribute to enriched levels of dissolved nutrients primarily in poorly flushed regions. Cumulative effects may occur in combination with other anthropogenic sources of nutrients and should not be neglected in the development of mariculture activities since they may lead to undesired effects of eutrophication.

In the present approach the carrying capacity for floating net cage fish farms within a domain is proposed to be equivalent to emission rates of total dissolved nitrogen (TDN) not exceeding 1% of the total dissolved nitrogen flux entering the domain. This threshold constitutes a pragmatic approach which is currently under discussion (Rosenthal, 2006). The load of total dissolved nitrogen is computed by multiplying the total water inflow with the corresponding concentration of total dissolved nitrogen.

<u>Farm placement</u>

From the suitability analysis and carrying capacity based on particulate emissions the most suitable farm locations are identified and dedicated to an environmentally sustainable production rate at local scale. However the number of farms is limited to the size of the suitable area. A distance from neighbouring farms is chosen in order to prevent overlapping and thus cumulative deposition of particulate matter which may exceed the critical deposition thresholds. Subsequently, the total production of all farms should not exceed the carrying capacity as determined for dissolved nutrients.

CASE STUDY: PEGAMETAN BAY, BALI, INDONESIA.

The study area

The DSS is exemplarily implemented for Pegametan Bay, situated at the northwest coast of Bali, Indonesia (8.13°S 114.6°E) for the farming of Tiger Grouper (*Epinephelus fuscoguttatus*) in floating net cages. Traditional floating net cage cultures typically comprise a set of individual cages of 3x3x3 meters placed in wooden rafts.

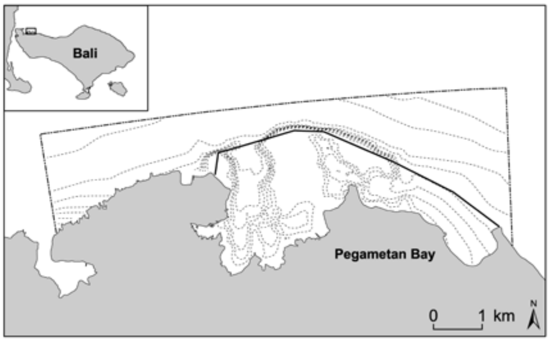

Figure 2: Pegametan Bay, Bali, Indonesia. The study area indicated by the outer boundary and depth contours. The solid black line shows the effective reef area.

Suitability analysis

<u>Suitability Criteria</u>

The FAO (1989) published a series of suitability criteria for finfish culture practice in South East Asia. These criteria have been adopted for suitability analysis in tropical regions by several studies (Mayerle et al. 2006; Halide et al. 2009). Additional recommendations for cage aquaculture regarding legislative and coastal management measures have been well documented (Ross et al. 1993; GESAMP 2001; Beveridge 2004). The adopted suitability criteria are presented in Table 1.

Table 1: Suitability parameters and criteria taken for Tiger Grouper (*Epinephelus fuscoguttatus*) grown in floating net cages.

Indicator	Parameter	Units	Allowable	Optimum
Physical	Minimum cage depth	m	> 6	> 8
	Maximum mooring depth	m	< 25	< 20
	Exposure to maximum currents	m/s	< 1	< 0.5
	Flushing by mean currents	m/s	> 0.01	0.2 – 0.5
	Exposure to maximum waves	m	< 1	< 0.6
Water quality	Water temperature	°C	20 – 35	27 – 31
	Salinity	g/l	15 – 35	26 – 31
	Dissolved oxygen	mg/l	> 4	> 5
	pH		7 – 8.5	7.8 – 8.5
	Secchi depth	m	> 2	> 4
	Ammonium	mgN/l	< 1	< 0.5
	Nitrite	mgN/l		< 4
	Nitrate	mgN/l		< 200
	Phosphate	mgP/l		< 70
	Suspended matter	mg/l	< 10	< 5
Coastal use	Distance to harbours	km	> 0.2	> 0.5
	Distance to navigation lines	km	> 0.2	> 0.5
	Distance to industrial areas	km	> 0.5	> 1
	Distance to touristic areas	km	> 0.3	> 2.5
	Distance to river	km	> 0.5	> 1
	Distance to land based discharges	km	> 0.5	> 1
	Distance to used perimeters	km	> 0.2	> 0.4
	Identified risks	Yes/No	No	No

<u>Physical parameters</u>

A 2DH numerical model was set up for the study area applying a curvilinear grid with a resolution of 35-45m. Water depths and topography were compiled from measurements, nautical charts and a global relief model. The model was driven by time series data for water level, current velocity and wave conditions provided by a nesting sequence of two larger models initially driven by astronomical constituents. Validation of modeled water levels resulted in a good fit with a mean average error of 0.06m and 0.05m and a standard deviation of 0.05m and 0.06m, when compared to water level measurements from two tidal gauges deployed in the bay.

Physical parameters were taken from the hydrodynamic model results as a statistic during a neap to spring tidal cycle. Water depths range between 0.5 and 150meters with a tidal range of ~1.7m resulting in minimum and maximum depths as required by the suitability analysis. Maximum current velocities did not exceed 1m/s within the model area. Mean current velocities were limited to ~0.1m/s in the center and eastern domain. Mean current velocities in the western inner bay did not exceed ~0.01m/s.

Significant wave heights were calculated for the curvilinear grid for a common and a worst-case scenario with prevailing wind speeds of 6 and 14m/s from northern direction. The worst-case scenario has a reoccurrence probability of once every 2 years, based on a wind time series (NOAA/OAR/ESRLPSD 2009)**.** Wave action was highest in the unsheltered area where simulated significant wave heights were below 1m under common conditions and reached 2.5m under extreme events.

Water quality

Measurements were done *in situ* at seven representative stations fortnightly for water temperature, salinity, dissolved oxygen, pH and Secchi depth from January 2008 until October 2008. Water quality samples were taken at two stations situated in the eastern and western gully in December 2008. Laboratory analysis was carried out for suspended matter, total ammonia nitrogen, nitrate, nitrite, and phosphorus. Available water quality information was averaged for the entire domain. The standard deviations were used as a correction for conservative assessment, resulting in a single value for each parameter representing the entire domain. For the observed parameters the level of water quality fully complied with the criteria for the targeted finfish cultures.

Coastal use

A field survey was conducted to identify cultivation and vegetation types along the coast. Populated, industrial and touristic areas were mapped. Several land-based discharges from semi intensive shrimp farms were found. Additionally two small rivers are located in the western part of the study site. About 13ha of seaweed culture is situated in the center. A touristic area is present 3km east of the study site. Harbours, industry and ship traffic lines were not present within the vicinity of the study site. There was no indication of potential risks such as sediment run off due to a lack of vegetation and substantial erosion.

Suitability

An overlay of the thematic grids from the above-described information indicated a suitable area of 122.4ha covering 5.5% of the study area (Figure 3a). This scenario considers worst-case wave exposure. By contrast, reduction of wave exposure generated by mean wind speeds of 6m/s result in a suitable area of 279.8ha or 12.6% of the study area as shown in Figure 3b.

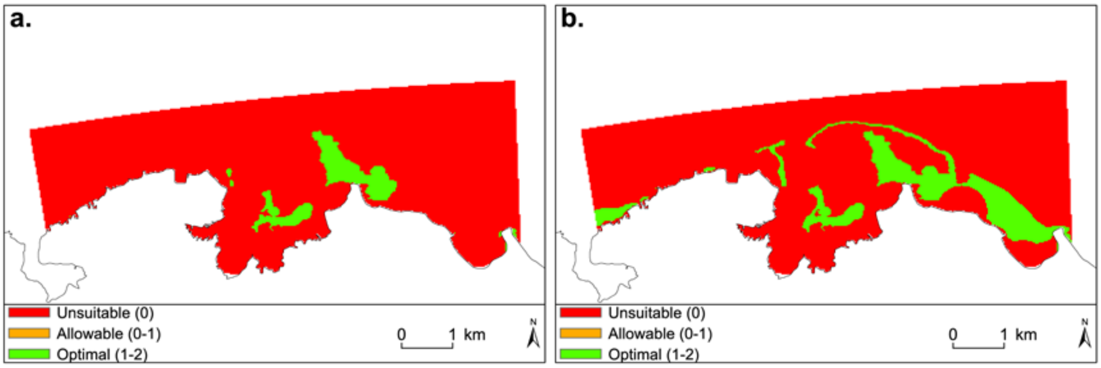

Figure 3: Maps for Pegametan Bay show suitable areas with a minimized risk of waves (a) and an expanded area with risk of waves (b).

Sustainability analysis

Farm emissions

Average daily farm emission was estimated for the production of one metric tonne of tiger grouper (*Epinephelus fuscoguttatus*) fed with trash fish. A feed conversion ratio of 6.5 was assumed resulting in a feeding rate of 17.79kg feed per day in an annual average. Feed and fish composition were taken to be 13.1% C and 3.95% N of the fresh weight (Alongi, 2009). 50% of the given feed, i.e. 1.14kgC/day, is assumed to be directly lost to the environment (Wu 1995). From the carbon consumed, a percentage of roughly 20%, 0.23kgC/d was supposed to be excreted as faecal matter (Hevia et al. 1996). Leung et al. (1999) reported that 63.9% of consumed nitrogen is excreted in dissolved form, mostly as ammonia. This corresponds 0.23kgN/d.

Deposition modelling

The particulate organic carbon was assumed to settle at 2.65 and 2.05cm/s for faecal and wasted feed, respectively (Chu 2002). Critical shear stress for sedimentation was indicated to be 0.004N/m² (Cromey 2002). Mineralisation was neglected in the application of this model since the settling in the shallow coastal area were assumed to be shorter compared to those of mineralisation. Estimated emissions for a production of 1 tonne/year were discharged within the model at 39 random points with different hydrodynamic character. DV values for all points ranged between 0.05 and 2. Model runs were repeated for productions of 5, 20 and 40 tonnes/year.

Carrying capacity based on particulate emissions

Modelled maximum deposition rates within a radius of 150m of the discharge point showed a linear relationship with increased productions rates. From this relationship the production rates at deposition thresholds of 1 and 5gC/m^{2}d were deduced.

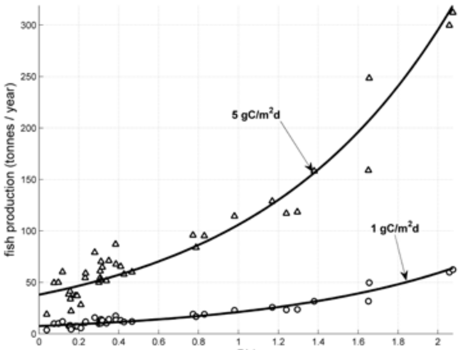

Figure 4: Relationships between the hydrodynamic character DV and the production rates reproduced by the deposition modelling approach.

In a next step the computed carrying capacity was related to the DV at different locations, resulting in an exponential relationship as shown in figure 4. Fitted exponential curves showed a regression of 0.91 (n = 39), and a mean error of 2.46 and 12.32 tonnes per farm per year for thresholds of 1 and 5gC/m²d, respectively. Production maps were then computed from DV values of the entire domain as shown in figures 5 a-d. A threshold of 1gC/m²d led to a production range of 9-30±2.46 tonnes/farm/year locally. A threshold of 5gCm²d led to a production range of 43 to 150±12.32 tonnes/farm/year within the area suitable for the targeted form of mariculture. For the extended suitable area, production ranges of 9-73±2.46 and 42 to 364±12.31 were found for 1 and 5gC/m²d, respectively.

The total allowable production rate of the entire area is dependent on the available area and the spacing between farms required to prevent cumulative effects of sediment pollution. Figures 4 a through d show scenarios with spacing of 200m and 300m between farms: Within the suitable area, a spacing of 200m would allow a production of 364-1824 tonnes per year divided over 30 farms (a), an increased spacing of 300m results in an annual production of 210-1050 tonnes per year from a total of 17 farms located in the suitable area (b), an expansion of the suitable area, involving risk of waves, and keeping a spacing of 200m results in a production of 1102-5512 tonnes per year over 61 farms (c) and a production of 594-2971 tonnes per year divided over 61 farms with a spacing of 300m (d).

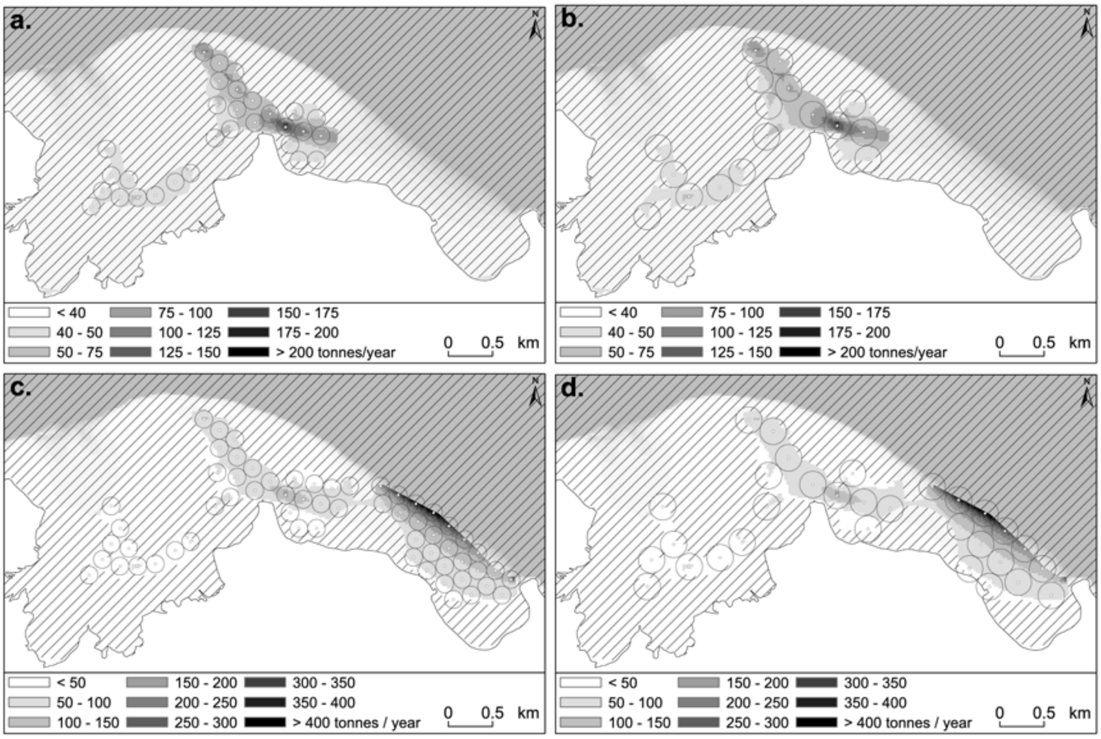

Figure 5: Production rates for a deposition threshold of 5gC/m²d. Proposed farm arrangements within the suitable area are shown at a spacing of 200m (a) and 300m (b). Farm arrangements within the expanded suitable area, involving a risk for waves is shown with a spacing of 200m (c) and 300m (d).

Sustainability based on dissolved nutrients

For the potential fish farming site (effective area following the reef as shown in figure 2), flow rates over the cross section perpendicular to the main current directions were computed from the hydrodynamic model results and multiplied with measured nutrient background concentrations to calculate the hydrodynamic nutrient flux. The daily inflow of water for neap and spring tide were 9.94E+7 and 1.65E+8m³/d, respectively. The average total dissolved nitrogen concentration calculated from 7 samples taken at the northern boundary of the study area was 0.1239±0.03641mg TDN/l. The resulting dissolved nitrogen flux accounted for 12320±3612 and 20402±5994kgTDN/d for neap and spring tides, respectively. Maximum tolerable fish farm emissions of 1% of the total dissolved nitrogen flux (i.e. 123.2±36.12 for neap and 204.02±59.94kg TDN/d for spring tide) divided by the TDN load derived from one tonne of fish produced would result in a carrying capacity of 529±156 tonnes/year and 876±258 tonnes/year for neap and spring tide, respectively. Considering an entire cycle one can thus assume an average allowable production capacity of 703±207 tonnes per year. The carrying capacity estimates based on total dissolved nitrogen are thus in the same range as those calculated from the deposition rates of organic carbon (except for scenario c).

CONCLUSION

The present study used criteria for suitability, farm emissions and thresholds that were specific for farm type, fish species and conditions in the particular tropical region. Assimilative capacity may vary spatially, within a domain. Hence thresholds should be taken conservatively and monitoring should be conducted at farms to verify and ensure environmental sustainability.

Criteria and thresholds which are used by the DSS can be adapted to any region and cultured species as desired. The present results show the possibilities of the DSS for advising governmental authorities in the implementation, environmental controlling and estimation of the overall carrying capacity for marine fish farming considering environmental sustainability.

Further development of the DSS is focussed on validation of the assumptions and estimations made. Subsequently, water quality modelling will be applied to assess the local impacts of dissolved nutrient emissions. Finally, verification of economic sustainability is in progress.

Acknowledgements. The authors would like to show their gratitude to the German Federal Ministry of Education and Research (BMBF), who support this project.

REFERENCES

Alongi, D. M., A. D. McKinnon, R. Brinkman, L. A. Trott, M. C. Undu, Muawanah and Rachmansyah. 2009. The fate of organic matter derived from small-scale fish cage aquaculture in coastal waters of Sulawesi and Sumatra, Indonesia. Aquaculture 295(1-2): 60-75.

Angel, D. L., P. Krost and H. Gordin. 1995. Benthic implications of net cage aquaculture in the oligotrophic Gulf of Aqaba. Improving the knowledge base in modern aquaculture. Proceedings of the Fifth German-Israeli Status Seminar of the German-Israeli Cooperation Programme in Aquaculture Research. Jerusalem, Israel, 18 July 1994. Spec.Publ.Eur.Aquacult.Soc. (25):129-173.

Beveridge, M. C. M. 2004. Cage Aquaculture, Blackwell Publishing.

Chu, J. C. W. 2000. Environmental Management of Mariculture: The Effect of Feed Types on Feed Waste. Regional Workshop on Sustainable Seafarming and Grouper Aquaculture, Medan, Indonesia.

Cromey, C. J., T. D. Nickell, K. D. Black , P. G. Provost and C. R. Griffiths. 2002. Validation of a fish farm waste resuspension model by use of a particulate tracer discharged from a point source in a coastal environment. Estuaries 25(5): 916-929.

Doglioli, A. M., M. G. Magaldi, L. Vezzulli and S. Tucci. 2004. Development of a numerical model to study the dispersion of wastes coming from a marine fish farm in the Ligurian Sea (Western Mediterranean). Aquaculture 231(1-4): 215-235.

FAO. 1989. Site Selection Criteria for marine Finfish Netacage Culture in Asia, UNDP/FAO Regional Seafarming Development and Demonstration Project, Network of Aquaculture Centeres in Asia. FAO Doc. NACA-SF/WP/89/13.
FAO. 2006. State of World Aquaculture. Rome, FAO.
Findlay, R. H. and L. Watling. 1997. Prediction of benthic impact for salmon net-pens based on the balance of benthic oxygen supply and demand. Marine Ecology Progress Series 155: 147-157.
GESAMP. 2001. Planning and management for sustainable coastal aquaculture development. GESAMP Reports and Studies No. 68, FAO: 90.
Gowen, R. J., N. B. Bradbury and J. R. Brown. 1989. The use of simple models in assessing two of the interactions between fish farming and the marine environment. Aquaculture - A Biotechnology in Progress. N. DePau, Jaspers, E., Ackefors, H. & Wilkins, N. European Aquaculture Society. Bredene, Belgium.
Halide, H., A. Stigebrandt, M. Rehbein and A. D. McKinnon. 2009. Developing a decision support system for sustainable cage aquaculture. Environmental Modelling & Software 24(6): 694-702.
Hargrave, B. T. 2002. A traffic light decision system for marine finfish aquaculture siting. Ocean & Coastal Management 45(4-5): 215-235.
Hargrave, B. T. 2003. Far-field environmental effects of aquaculture in aquatic ecosystems. A scientific review of the potential environmental effects of aquaculture in aquatic ecosystems. Volume I. Ottawa, Fisheries and Oceans Canada Science Sector. 2450: 131.
Hevia, M., H. Rosenthal and R. J. Gowen. 1996. Modelling benthic deposition under fish cages. J. Appl. Ichthyol. 12(1996): 71-74.
Leung, K. M. Y., J. C. W. Chu and R. S. S. Wu. 1999. Nitrogen budgets for the areolated grouper epinephelus areolatus cultured under laboratory conditions and in open sea cages. Marine Ecology Progress Series 186: 271-281.
Mayerle, R. and W. Windupranata. 2006. A Decision Support System for the Sustainable Environmental Management of Marine Fish Farming. Second International Symposium on Cage Aquaculture Asia (CAA2), Hangzhou, China.
NOAA/OAR/ESRLPSD. 2009. NCEP/NCAR Reanalysis 2 data. Retrieved 04.09.2009 from http://www.cdc.noaa.gov/.
Pérez Martinez, O., 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(4): 761-768.
Rosenthal, H. 2006 Personal communication.
Ross, L. G., E. A. Mendoza Q.M and M. C. M. Beveridge. 1993. The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. Aquaculture 112(2-3): 165-178.
Stigebrandt, A., J. Aure, A. Ervik and P. K. Hansen. 2004. Regulating the local environmental impact of intensive marine fish farming: III. A model for estimation of the holding capacity in the Modelling-Ongrowing fish farm-Monitoring system. Aquaculture 234(1-4): 239-261.
Wu, R. S. S., P. K. S. Shin, D. W. MacKay, M. Mollowney and D. Johnson. 1999. "Management of marine fish farming in the sub-tropical environment: a modelling approach." Aquaculture 174(3-4): 279-298.
Yokoyama, H., M. Inoue and K. Abo. 2004. Estimation of the assimilative capacity of fish-farm environments based on the current velocity measured by plaster balls. Aquaculture 240(1): 233-247.