Environmental Management (2010) 45:953–962
DOI 10.1007/s00267-010-9467-5

A Management Tool for Assessing Aquaculture Environmental Impacts in Chilean Patagonian Fjords: Integrating Hydrodynamic and Pellets Dispersion Models

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Received: 9 September 2008 / Accepted: 2 February 2010 / Published online: 24 March 2010

Abstract This article introduces a management tool for salmon farming, with a scope in the local sustainability of salmon aquaculture of the Aysen Fjord, Chilean Patagonia. Based on Integrated Coastal Zone Management (ICZM) principles, the tool combines a large 3-level nested hydrodynamic model, a particle tracking module and a GIS application into an assessment tool for particulate waste dispersal of salmon farming activities. The model offers an open source alternative to particulate waste modeling and evaluation, contributing with valuable information for local decision makers in the process of locating new facilities and monitoring stations.

Keywords Salmon farming · Pollutant modeling · Particulate waste management · Lagrangian models · Decision support system

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Introduction

Contemporary human exploitation of world marine ecosystems appears to be unsustainable. Over 75% of the natural fish stocks are considered fully exploited or over-exploited (Food and Agricultural Organization 2007). Direct impacts over biodiversity, habitat destruction and waste disposal, along with climate change indirect effects -and a possible synergy between these factors- allow predicting the collapse of all harvested taxa by the year 2048, if we sustain today's trend of use and extraction (Harley and Hughes 2006; Worm and others 2006). On the other hand, fish consumption has duplicated since 1960 and now it's the fastest growing food industry worldwide (Food and Agricultural Organization 2007). In this context, fish farming—responsible for more than 70% of this growth—appears as a proper way to reduce human pressure over world fish stocks. However, carnivorous species farming (e.g. salmon, trout) requires large food inputs, producing a series of local impacts on marine ecosystems, converting them in a mixed blessing for world fisheries. On the negative side, some aquacultures, including salmon farming, raises the demand for some pelagic fish species (e.g., Chilean mackerel) used for fish oil and flour (Naylor and Burke 2005; Naylor and others 2003; Naylor and others 2000).

In general terms, the marine phase of the salmon farming productive cycle consist of an accelerated and controlled growth of juvenile individuals, until they obtain an appropriated weight for their processing and commercialization. Fish are maintained in floating cages, settled in sheltered areas (like fjords, channels and inner seas), and fed with food pellets made of a variable fraction of marine fish oil and fishmeal. Along with the pressure over pelagic fisheries, salmon farming produces a series of environmental impacts over marine ecosystems where the cages are located. They are, in summary: (1) waste disposal over the water column and bottom, like food pellets, fish feces and antibiotics, (2) invasion by exotic fish species and pathogens every time fish escape from cages—when salmon aren't native species, like in Chile—and (3) habitat destruction (Cabello 2006; Naylor and Burke 2005; Naylor and others 2003; Soto and Norambuena 2004). These impacts could obscure salmon farming's contribution to reduce pressures on natural fish resources. In this context, it could be argued that salmon farming is now in a crossroad between been against or in favor of sustainable development of world fisheries. The path it shall take will depend on their fishmeal and oil use policies (Naylor and others 2000), and how it will manage local impacts related to their activities. It is toward the later that we have focused this article.

Lagrangian Models and Their Use in Salmon Farming Management

One of the main causes of local environmental impacts of salmon aquaculture is particulate waste disposal, mostly as food pellets and feces (Ervik and others 1997; Karakassis and others 2002, Reid and others 2009). These particles usually deposit in ocean's bottom mainly below and around the cages, distressing the system in various ways: (a) anthropogenic inputs of organic carbon, nitrogen and phosphorous, sometimes surpassing the carrying capacity of the system, (b) increase of primary productivity, modifying bottom's vegetal community structure, (c) negative impacts over benthos biodiversity and (d) the formation of an anoxic layer in the sediments under the cages (Corner and others 2006; Cromey and others 2002; Findlay and others 1995; Karakassis and others 2002; Soto and Norambuena 2004).

A widely adopted approach to particulate wastes analysis is their dynamic simulation, mainly via two approaches: GIS models (Perez and others 2002; Corner and others 2006) and lagrangian particle-tracking models (Cromey and Black 2005; Cromey and others 2002). The later simulate the dispersion and sedimentation of particles in the ocean bed. Coupling particle-tracking models with other numerical models (e.g., hydrodynamic, benthic or atmospheric models), involving additional biogeochemical and ecological processes, contribute to a more integrated assessment of salmon farming local impacts (Corner and others 2006; Cromey and Black 2005; Cromey and others 2002; Panchang and others 1997; Perez and others 2002).

A Broader Context

However, in a scenario where aquaculture contributions to sustainable fisheries depends on the industry management practices, numerical models like the one presented here will not gain enough relevance until they are put into a wider context, allowing the application of their results outside the academic field. A management framework able to provide this wider context is the Integrated Coastal Zone Management (ICZM). This management framework understand the relationship between nature and society as a process where perturbations generated from the later alter some ecosystem functions, eventually affecting the flux of ecosystem services to society, generating negative impacts over it, related to the DPSIR (Driver-Pressure-State-Impact-Response) approach (Turner 2000; Turner and Salomons 1999). This approach provided the conceptual framework needed for this research, applied specifically to salmon farming (Fig. 1)

ICZM also provides support for stakeholder involvement in any of the multiple stages of project development (Christie and others 2005; de Araujo and Bramwell 1999). Stakeholders' involvement in the research process brings a series of benefits for both parties, researchers and decision makers; (1) Considering the high field data requirements for numerical models needed to set model's initial/boundaries conditions and for the validation process, government stakeholders participation –and their data bases- are a key element in the data gathering period, (2) the capacity to identify each of their administrative, technical and institutional capabilities, key information when generating public research reports and decision support systems to final users (Pedersen and others 2005), and (3) the creation and definition of modeling scenarios is facilitated, linking research with stakeholders' specific interests (Hanson and others 2006). Thus, modeling tools that offer the possibility of wide stakeholder's involvement (e.g., Marin and others 2008; Delgado and others 2008) should make an important contribution to the integrated management of coastal zones.

In this context, the main objective of this article was to describe a management tool based on a three-level nested, coupled, circulation-lagrangian model to assess the fate of particles generated at salmon cages. The results of this model are further integrated into a management tool, programmed in ArcView 3.3 Geographic Information System, in the form of an assessment tool for the design of water quality regulations projects. Although we have applied and tested this tool to the Chacabuco bay area in the southern Chilean fjord, its application is system-independent and, as such, it could be used to manage salmon farming in other areas of the world.

Study Area

Chacabuco bay [45°28' S, 72°49' W] is an embayment located in the eastern part of Aysen Fjord (Southern Chile),

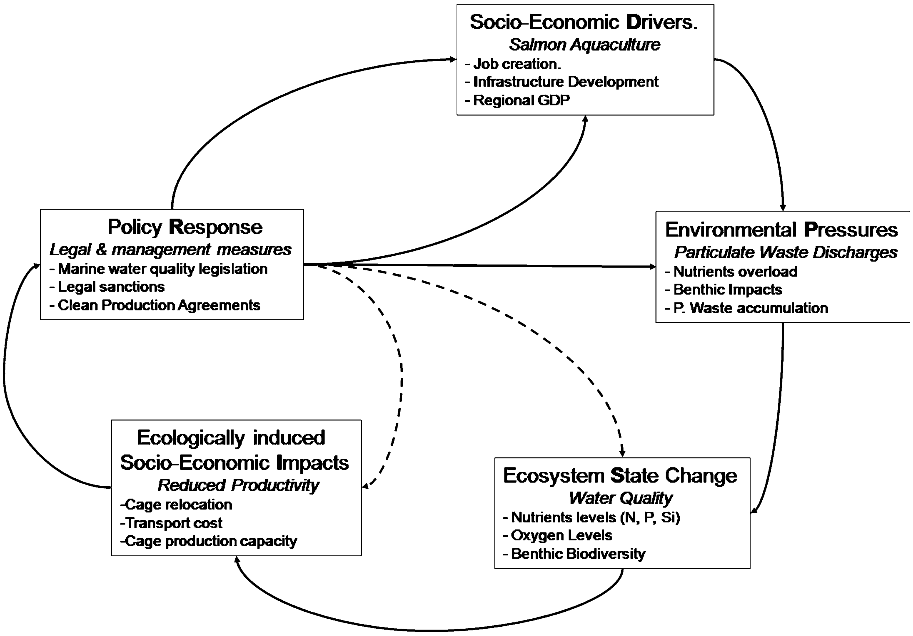

Fig. 1 DPSIR cycle adapted to Aysen's local socio-ecological dynamics (Adapted from Turner and Salomons 1999)

8 km south of the outlet of the homonym river (Fig. 2). The main human settlement in the area is Puerto Chacabuco (1442 inhabitants). Situated on the eastern side of the bay, it's the most important marine commercial and touristic port of the region. Being the main entrance for all kind of goods, Puerto Chacabuco is a key element in the productive cycle of almost every economic activity of the Aysen region, especially salmon farming, since it is the starting point for the exports of processed fish to Europe, USA and Japan. In this context, the water quality of the bay has been affected by several industrial sources, mainly: (1) five salmon farming complexes operating in the bay area, (2) industrial wastes from fish processing industries and (3) leaks and spills associated with oil and mining port activities (e.g. hydrocarbons, minerals).

Methods

Hydrodynamic Models

Hydrodynamic models utilized in this work were developed with the open-source MOHID Water Modeling System v.4.6 (Braunschweig and others 2004; Neves 1985). A 3-level nested modeling structure was chosen in order to simulate the complex tide signal of the fjord system, reduce numerical errors and to enhance model stability (Fig. 2). The first level, Fjords, is a barotropic, single-layer sigma model covering the northern part of Chilean fjords, between 41°S and 46°S, with an horizontal grid definition of 2.2 Km. The main purpose of this level was to provide the tidal conditions, obtained in turn from the FES2004 model (Lyard and others 2006), to the lower level models. The second level in the nested structure (Aysen) is a model covering the area of the Aysen Fjord. It is also barotropic, but besides incorporating tides from the Fjords model, it includes the three most important fresh water discharges (rivers) of the fjord. These two models have been described in detail by Marin & Campuzano (2008).

The third level in the hydrodynamic modeling structure, Chacabuco, covers the inner area of the Aysen Fjord. It is a baroclinic model, with a cartesian geometry of 24 vertical layers. Its horizontal grid resolution is approximately of 100 m, and it was over this level that the lagrangian particle-tracking module was implemented. The numerical grid was generated using bathymetric and coastline data from Armada de Chile (Chilean Navy). Initial conditions—salinity and temperature—where defined as profiles, with data obtained from CIMAR program (Silva & Palma 2008), while boundary conditions where obtained from two sources; river inputs flows where generated based on information from the National Water Directorate[1] and tides where obtained from the father model (Aysen).

Every model was initialized for 30 summer days with the purpose of stabilizing their water level. Then, with tides stabilized, we executed another 30 days run to initialize water properties (temperature and salinity). Finally, with tide signal, temperature and salinity stabilized, a final 7-day run was implemented to simulate food and fecal pellets dispersion in the bay area. The time span of the runs was from January to March. Table 1 shows the main characteristics of each of the three models.

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[1] www.dga.cl.

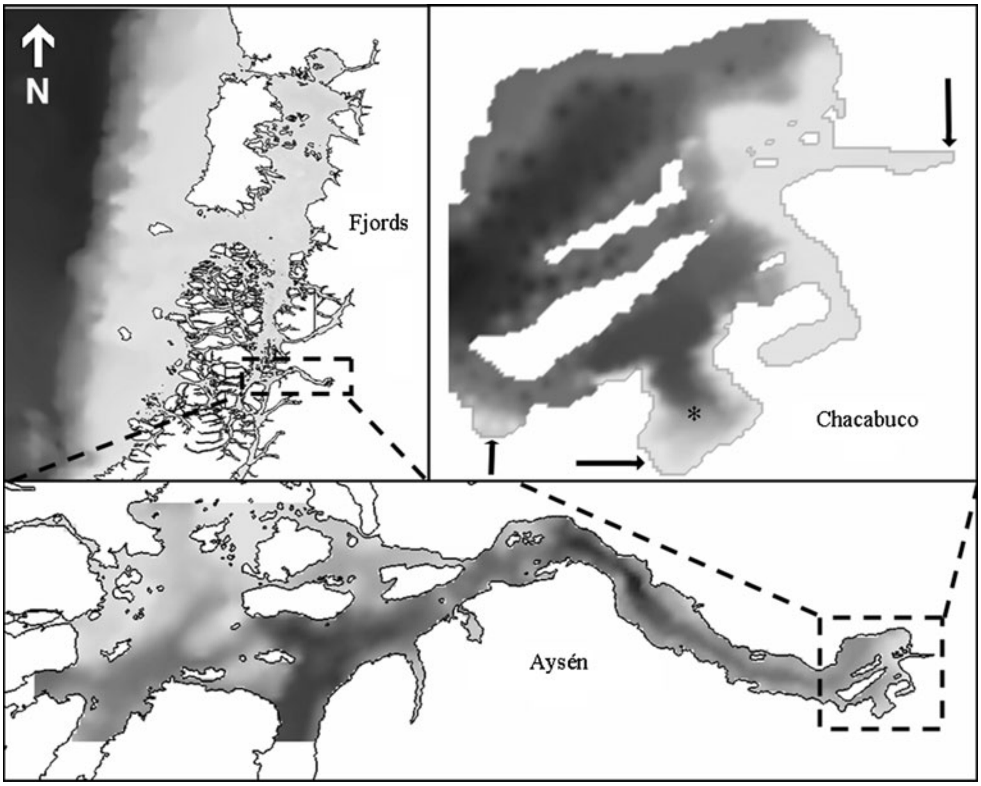


Fig. 2 Areas covered by the three level nested modeling structure. *Black arrows* indicate the position of the water discharges in the Chacabuco Model. The "*" indicates the location of Chacabuco Bay and the location of tide and salinity sampling station used for model validation. *Darker colours* represent deeper waters

Table 1 Main properties of the three nested model system

Model	Nesting level	Grid definition (Km)	Geometry	Type	Discharges	Tides
Fjord	1	2.2	Cartesian, 1 layer	Barotropic	No	FES2004
Aysen	2	0.5	Cartesian, 1 layer	Barotropic	Yes	Fjord model
Chacabuco	3	0.1	Cartesian, 24 layers	Baroclinic	Yes	Aysen model

Lagrangian Particle Tracking Module

The dispersal of salmon farming's particulate wastes was simulated with the Lagrangian Module of the MOHID Water Modelling System. In what follows we describe the parameterization and assumptions used in relation to salmon farming particulate waste loads, their dispersal in the water column and simulation time.

Discharge Volume

A fish density of 10 Kg m^{-3}, for every 6000 m^3 cage, was considered for food pellets output with a food/biomass ratio of 1.2. Only 5% of this load was considered to go below the cage's bottom and fall through the water column. We have further assumed that half of these wasted food pellets were eaten by local marine fauna (Cromey and others 2002). This pellet mass (in Kg) was then converted to particles assuming a caliber 2500 pellet (0.9 g per pellet, EWOS Chile Website 2010). The final number of particles was calculated as 450 particles per cage every two hours for food pellets, and 2250 particles per cage every two hours for fecal pellets, assuming a feed/fecal pellets ratio of 1/5 (Reid and others 2009).

Sedimentation Velocity

Previous work has shown that sedimentation velocity depends on particle size (Perez and others 2002) and that food and fecal pellets suffer changes in their size as they descend through the water column (Chen and others 1999, Reid and others 2009). Here we have simplified this process applying a constant sedimentation velocity. The values are showed in Table 2. The main purpose of this simplification was to reduce computing time and hardware requirements, given the rather large number of particles tracked in our simulation ($>10^6$).

Table 2 Default values and sensitivity analysis scenarios

Parameters	Units	Default values	Resuspension		Sedimentation	
			E1	E2	E3	E4
Critical shear stress of erosion	Pa	0.02	0.01	0.04	–	–
Critical shear stress of deposition	Pa	0.004	0.002	0.008	–	–
Erosion rate	$gm^{-2}\ s^{-1}$	0.005	0.0025	0.01	–	–
Sed. velocity food pellets	ms^{-1}	0.128	–	–	0.096	0.064
Sed. velocity fecal pellets	ms^{-1}	0.032	–	–	0.015	0.066

For every scenario (*E#*), defaults parameters where modified to fit a range of values founded in literature

Salmon Production Cycle

Salmon farming involves different fish densities for each stage of the production cycle, reaching a maximum at the fifth year of operation, with densities between 9 and 15 Kg m^{-3}. For the purposes of this model we chose a fixed density (10 Kg m^{-3}) corresponding to a high production stage. Discharges were tracked subsequently every 2 hours.

Simulation Time

To determine the length of the simulation, 7, 14 and 21 days runs where tested. When checking the results for every discharge origin, we noticed that after the second day of discharges, the area of dispersion didn't change significantly. In fact, while shallower origins showed constant resuspension, the deepest origins (1, 2 and 3, see Fig. 4) didn't showed any measurable difference. Accordingly, we choose a 7 day simulation to save calculation time and hardware requirements. In any case, the stability of the area of dispersion in MOHID is dependant on bottom flow velocity, shear stress and erosion parameters, therefore simulation time-span should be assessed case to case.

Consolidation

The model does not consider food or fecal pellets consolidating in the sediments. There is no enough available information about sediments in the area of study. A no-resuspension scenario was added to the sensitivity analysis to test this assumption.

As a general note, we based our assumptions in literature information because there was no local field data on food or fecal pellets' nature and dynamics, and salmon producers did not provide any environmental information during this research.

Sensitivity Analysis

Sensitivity analysis was done defining default values for every parameter tested (default run), and then adjusting them within the ranges found in literature to create sensitivity scenarios (Cromey and others 2002; Chen and others 1999; Panchang and others 1997; Perez and others 2002; Wiberg 2004, Reid and others 2009). Four scenarios where defined, as shown in Table 2. The variable over which we performed the sensitivity test was the area covered by particles on day seven of simulation (A_7) under each cage, using ArcGIS 9.3 for area measurements. Model sensitivity (S_x) was evaluated as the change in "A_7" relative to changes in a model parameter "P" (Huntley and others 1987), using equation (1).

$$S_x = \frac{(A_{7s,x} - A_{7\mathrm{def}})/A_{7\mathrm{def}}}{(P_{s,x} - P_{\mathrm{def}})/P_{\mathrm{def}}} \tag{1}$$

where $A_{7s,x}$ is the value for A_7 for the x scenario in the sensitivity analysis, and $A_{7\mathrm{def}}$ is the value for A_7 on the default run. $P_{s,x}$ correspond to the value of parameter P for a given sensitivity scenario x, while P_{def} is the default value of the parameter.

Management Tool

The management tool generated is a modified ArcView© 3.3 (ESRI Inc.) interface (programmed using AVENUE scripts) that shows, in a simple and user-friendly way, the combined results of the hydrodynamic and particle-tracking model in a Geographic Information System (GIS) environment. Custom buttons where added to show food and fecal pellet dispersal, relevant hydrodynamic data and GIS coverages showing the location of sewage discharges, food processing industries' location, among other relevant information (dock location, towns streets, etc). Help text and button information were translated to local language (Spanish) to improve user experience. During the development of the tool, local manager's capabilities and requirements were checked to improve tool's usability and to fulfill their information requirements.

Stakeholder Participation

In order to improve and facilitate data gathering, a series of agreements where signed with local government authorities (e.g., National Environmental Commission, National Water Directorate and Regional Planning Secretariat). In order to take into account decision maker opinions, capacities and information requirements, the management tool was designed based on the results of the participatory process developed under the ECOMANAGE Project (Marin and others 2008; Delgado and others 2008).

Results

The Chacabuco hydrodynamic model was validated with respect to salinity and water level. The model is capable of reproducing the typical halocline present in the Aysen fjord (Fig. 3), with the river flowing seaward through the upper level of the water column. When comparing water levels produced by the model with real values taken from mareographic station located inside Chacabuco bay, the results shows a good fit, with an r^2 of 0.94 (Marin and Campuzano 2008). Thus, the hydrodynamic model is able to simulate the main characteristics of the estuarine system in the Chacabuco bay area. Therefore, the "event" validated hydrodynamic model -see discussion for details- was used to study the spatial dispersion of particulate wastes coming from salmon farming activities in the bay, using MOHID lagrangian module.

The results of the lagrangian particle-tracking module (solid waste dispersal after 7 days of simulation of five cages throwing 2700 particles every 2 hour, 450 of food pellets and 2250 of fecal pellets) are shown in Fig. 4. The majority of the origins showed particles dispersing mostly beneath the cages or in distances between 100 m and 300 m from the cage's center, depending on the depth of the cage's location. Food pellets dispersion results shows that cages located in areas with depths deeper than 60 meters showed almost no resuspension and very limited dispersion, with particles just accumulating near the cages after the first discharge, even when we changed the models parameters to improve dispersion for the sensitivity analysis, indicating that these cages weren't specially affected by resuspension (Fig. 5). However, cages located in shallower areas (southern part of the bay) showed greater dispersion and higher sensitivity to parameter variation, especially those regulating resuspension (Fig. 5). On the opposite, fecal pellets' dispersion showed greater variability between scenarios, especially when we changed parameters related to sedimentation velocity on deeper origins. This results showed that solid waste dynamics vary between food and fecal loads, mainly because their differences in sedimentation velocity. Since food pellets reach the bottom after 6–12 minutes in the water column, resuspension should be the most important factor on their dispersion, while fecal pellets dispersion, given their lower sedimentation velocities (between 26 and 50 minutes descending through the water column), should be greatly affected by sedimentation velocity.

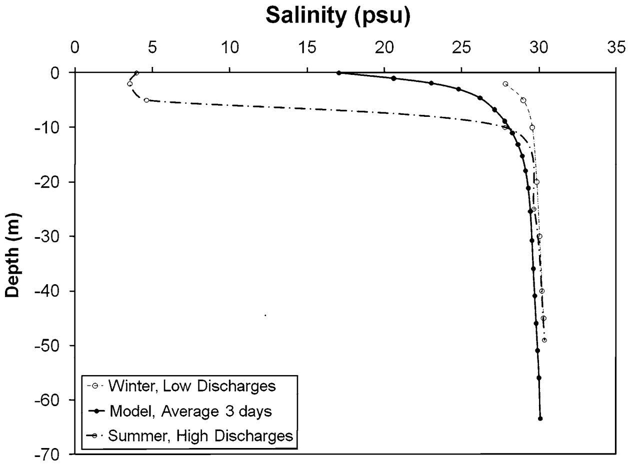


Fig. 3 Salinity values for average model results (*filled circle*) and available field data (*open circle*) for two seasons

The participatory process executed during the ECOMANAGE project identified several relevant issues about salmon aquaculture; (1) Government officials, industry executives and local population identified the salmon aquaculture industry as a regional socioeconomic driver (as in the DSPIR cycle, Fig. 1), (2) Available environmental and territorial planning studies identified Chacabuco bay as a fundamental component in the economic system of the Aysen region, (3) There is a huge gap of information about the system's carrying capacity and salmon aquaculture waste effects -in the watershed rivers' and in Chacabuco Bay- (Marin and others 2008; Delgado and others 2008). The final management tool (Fig. 6) was delivered to local decision makers in a custom installer with Spanish instructions.

Discussion

We have shown the development of a lagrangian particle-tracking model that can be used by salmon farmers and local decision makers, offering an open source alternative to the currently available commercial dispersion models. Our results show the spatial magnitude of particulate waste discharges in Chacabuco Bay, along with the main areas of food and fecal pellets deposition. This has already been used as valuable input information in current regional water quality regulations projects, facilitating the definition of the monitoring stations' location, providing a general idea of the spatial distribution of salmon farming impacts (Secondary Norms Committee, personal communication). Further developments of this tool could be used to assess

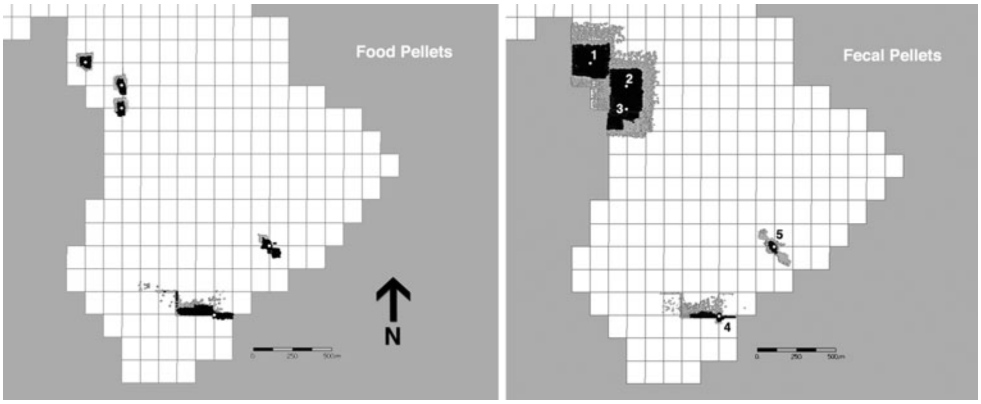


Fig. 4 Final spatial distribution of our 7-days simulation. *Darker particles* represent the outputs from the default simulation, while *grayscale* particles show results from the sensitivity scenarios. *White dots* indicate the location of the cages. *Left*: Results from food pellets dispersal. *Right*: Results from fecal pellets dispersal

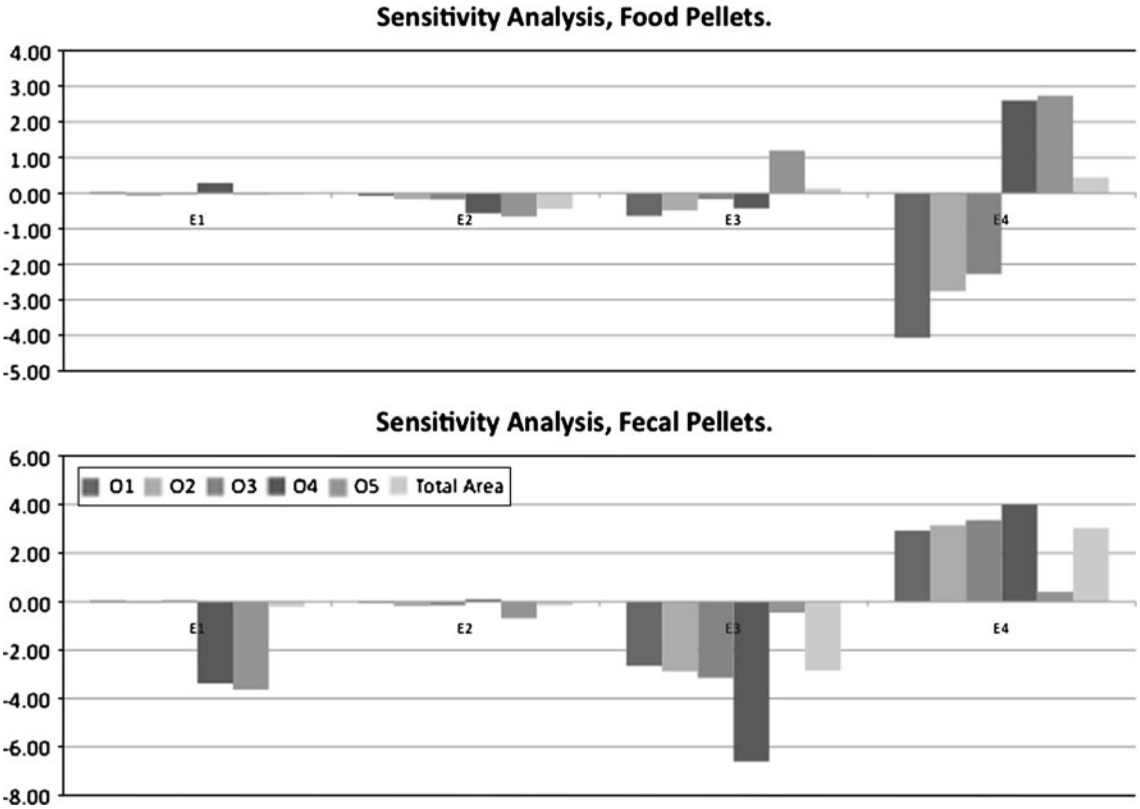
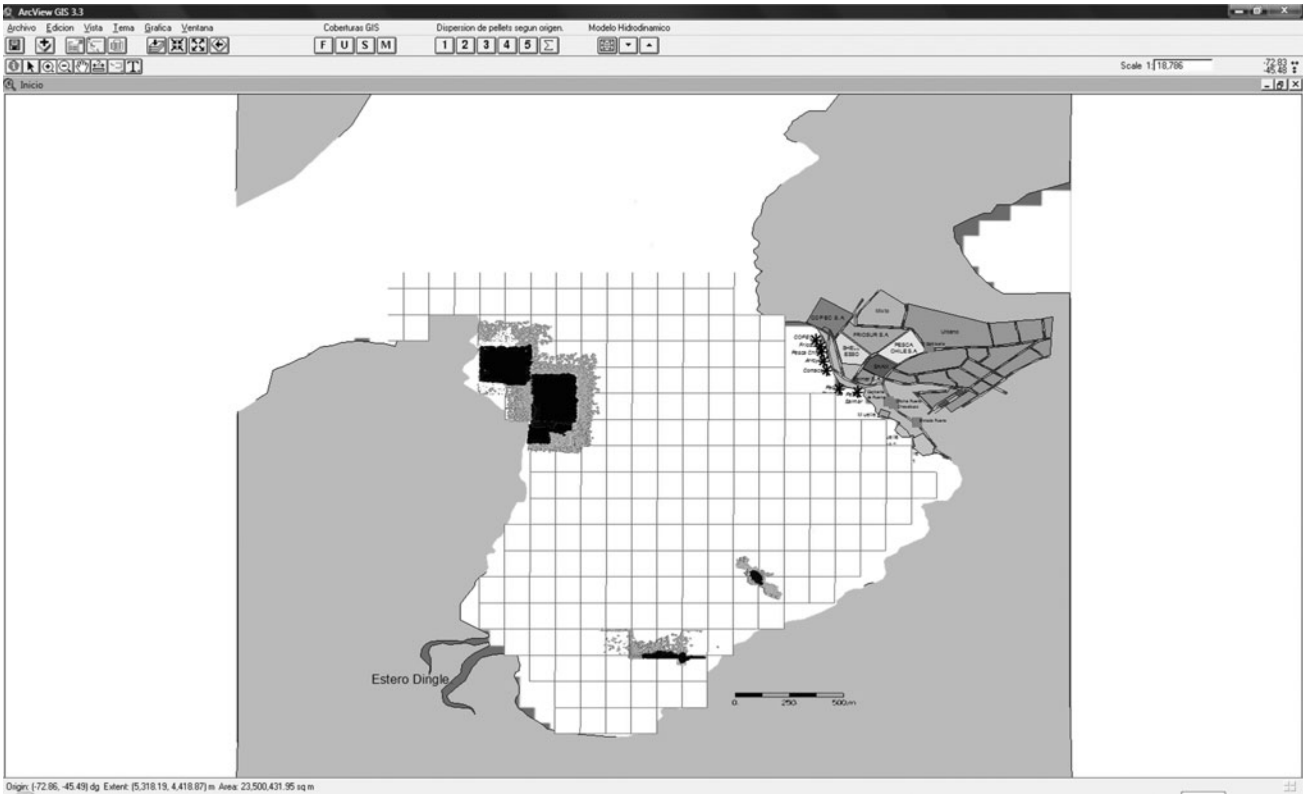


Fig. 5 Results of the sensitivity analysis. Sensitivity was calculated based on particle dispersion area for every origin, according to Huntley's formula (Huntley and others 1987). Higher values, either positive or negative, indicate high sensitivity of the model to variation in the parameters modified in every scenario (*E#*). Values near zero indicate that the model is insensitive to variations in these parameters. *O#* indicate origin number (see Fig. 4). *E#* denote every sensitivity scenario, detailed in Table 2

local ecological impacts associated to particulate waste originated from salmon farming. Ecological and water quality models are presently under development for the fjord area, modeling nutrients, oxygen and plankton dynamics, in order to provide a broader assessment of these environmental impacts.

When comparing our model outputs with previous work with a lagrangian approach (Cromey and Black 2005; Cromey and others 2002), the results are qualitatively similar. The DEPOMOD model has a validated dispersion module, showing between 13% and 22% of difference between modeled and observed values (Cromey and others 2002), and thus would be used as a reference in this comparison, an already proposed method of model validation (Rykiel 1996).

However, there are some important differences between these two models that should be taken into account before any comparison. First, sedimentation velocity in our model was defined constant (1.28×10^{-1} m s^{-1} for food pellets, 3.2×10^{-2} m s^{-1} for fecal pellets) during the whole simulation,



Scale 1: 18,786

-72.83
-45.48

Origin: (-72.86, -45.49) dg Extent: (5,318.19, 4,418.87) m Area: 23,500,431.95 sq m

Fig. 6 Snapshot of the customized ArcView interface for the management tool showing pellets 20 dispersal in Chacabuco bay. The tool has four different GIS coverage buttons, six pellets dispersal buttons and three buttons configured to show results of the hydrodynamic model

while DEPOMOD uses random generated rates taken from a determined range of values. The amount of particles simulated (1×10^6) is two order of magnitude above DEPOMOD (7×10^4, Cromey and others 2002). In fact, the volumes used in this study are similar to the real production values for particulate wastes discharges from Chilean salmon cages, according to EIA reports from salmon farmers.[2] Another important difference is the spatial and time scale of both models. While Cromey and others (2002) used a grid definition of 10 × 10 m, covering an area of 0.25 Km^2, here we used a grid of 100 × 100 m, covering an area of 147 Km^2. The time span of both simulations is also quite different. Our model ran for seven days, with particle discharges every two hours for five origins, while Cromey and others (2002) shows a 24 hour simulation with a single discharge at the beginning.

Despite the differences just mentioned, both models (DEPOMOD and MOHID) showed similar results in their particles' dispersal simulations. Cromey's work (Cromey and others 2002) showed that particle dispersal occurred mainly beneath the cages (0–100 m.), reaching a maximum distance of 200–300 m from the cage center. Our results, for comparable depths, showed the same pattern, but with maximum dispersal distance reaching 300–400 m. Thus, the simulation of salmon farming particulate waste dispersal using MOHID lagrangian module shows congruent results when compared with previous experiences with similar approaches but in different systems (Cromey and others 2002) and in general, with previous simulations of particulate waste dispersal (Corner and others 2006; Panchang and others 1997; Perez and others 2002). Therefore, this management tool offers an open source option to the modeling of particulate waste in the fish farming industry, with similar results to those generated by modeling systems currently available.

Even though we acknowledge the lack of a formal validation, because of the absence of available field data, but understanding that there are many ways to validate a model (Oreskes and other 1994), we consider that the management tool presented in this work, and the models in it, are partially validated in many ways, according to Rykiel (1996):

- This management tool was developed for local decision makers. Since they are already using it, the model is "operationally validated".
- The hydrodynamic model is capable of reproducing the dynamics of a Patagonian fjord, like a steep halocline and thermocline, the tide signal, and the two layer circulation structure of estuaries, thus is "event validated".

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[2] www.seia.cl.

- Given the level of field data available about what's happening under Chilean salmon cages (Chilean aquaculture's best kept secret, according to local NGOs[3]), and the knowledge about the Patagonian fjord system (CIMAR cruises, Silva & Palma 2008), this semi qualitative validation -since tides and salinity are formally validated- should be relevant enough.

This work presents the MOHID modeling system as an excellent framework to develop management tools for particulate waste assessment in coastal marine systems, according to the needs, capacities and requirements of local decision makers, with the ability to synthesizing data from numerous salmon farms and their cumulative effects, with relatively low fund requirements, a continuously updated open-source modeling software system and a growing online support community (www.mohid.com), conforming an excellent choice to environmental impact assessment of coastal system, specially for developing countries.

Finally, in order to improve the usability and acceptance of MOHID's lagrangian module as a solid waste dispersal model for aquaculture, further and deeper comparisons should be made versus field measurements and/or testing both models (DEPOMOD and MOHID) in the same system.

Acknowledgments This work was developed under the Project "Integrated Ecological Coastal Zone Management System" [ECO-Manage], financed by the Sixth Framework Programme (FP6) of the European Commission (EC) (contract n°: INCO-CT-2004-003715) (http://www.ecomanage.info). We thank Pamela Bachmann and three anonymous reviewers for their constructive comments on earlier versions of this manuscript.

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