A MANAGEMENT TOOL FOR SALMON AQUACULTURE: INTEGRATING MOHID AND GIS APPLICATIONS FOR LOCAL WASTE MANAGEMENT

A. TIRONI, V.H. MARIN AND F. CAMPUZANO

1 INTRODUCTION

Contemporary human pressures over world marine ecosystems could be unsustainable. Over 75% of the world natural fish stocks are considered fully exploited or over-exploited (FAO 2007). Direct impacts over biodiversity, habitat destruction, waste disposal and climate change indirect effects -and a possible synergy between these factors- (Harley and Hughes 2006) allow predicting the collapse of all harvested taxa by the year 2048, if we sustain today's trend of use and extraction (Worm et al. 2006). However, fish consumption has duplicated since 1960 and now it's the fastest growing food industry worldwide (FAO 2007).

In this context, fish farming -responsible of more than 70% of this growth- appears as a proper way to reduce human pressure over world natural fisheries. But, is this true for all types of aquaculture? Unfortunately no, farming of carnivorous species requires large food inputs and produces a series of local impacts on marine ecosystems, converting them in a mixed blessing for world fisheries (Naylor et al. 2000). Fish farming reduces the pressure over natural fisheries used for human consumption, but at the same time it raises the demand for some pelagic species (e.g Chilean mackerel) used for fish oil and flour, used in the elaboration of fish pellets. One of these forms of aquaculture is salmon farming (Naylor et al. 2000, 2003, 2005).

In general terms, the marine stage of 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 protected areas (like fjords, channels and inner seas), and fed with pellets made of a variable fraction of marine fish flour and oil. Aside from the pressure over pelagic fisheries, salmon farming produces a series of environmental impacts over marine ecosystems where the cages are installed. They are, in a short 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 and, as a result of these processes, (3) habitat destruction (Naylor et al. 2003, 2005, Miranda and Zemelman 2002, Cabello 2006). These impacts could obscure salmon farming's contribution to reduce pressures on natural fisheries 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 fish flour and oil use policies (Naylor et al. 2000), and how it will manage local impacts related to their activities. It is toward the later that we have focused this work.

2 LAGRANGIAN MODELS AND THEIR USE IN SALMON FARMING MANAGEMENT

A common cause of most salmon farming local environmental impacts is particulate waste disposal in the form of food pellet and feces- to the water column and bottom. These particles usually deposit in the vicinity of cages, distressing the system in various ways: (a) artificial inputs of organic carbon, nitrogen and phosphorous, (b) increase in primary productivity, modifying bottom's community structure, (c) negative impacts over benthos biodiversity and (d) the formation of an anoxic layer in the sediments under the cages (Corner et al. 2006, Cromey et al. 2002, Findlay et al. 1995, Soto and Norambuena 2004)

A widely adopted management tool for this kind of particulate wastes is their dynamic simulation by means of lagrangian particle-tracking models (Cromey et al. 2002, Cromey and Black 2005). These models simulate the dispersion and sedimentation of particles in ocean's bottom. Coupling these with other numerical models, involving additional physical, biogeochemical and ecological process, could contribute to a more integral assessment of salmon farming local impacts (Corner et al. 2006, Cromey et al. 2002, Cromey and Black 2005, Panchang et al. 1997, Perez et al. 2002) . We implemented, as one of ECOMANAGE activities, a three-level nested, coupled circulation-lagrangian model to assess the fate of particles generated at salmon farming sites, one of the main economic drivers of the Aysén fjord region. We have applied this tool to the Chacabuco bay area inside the fjord.

3 METHODS

3.1 Hydrodynamic models

Hydrodynamic models utilized were developed with the open-source software MOHID Water Modeling System (Leitão et al., this volume). 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. 1). 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 a definition of 2.2 km. The main purpose of this level was to generate the tidal components, obtained from the FES2004 model (Lyard et al. 2006), for the lower level models. The second level in the nested structure (Aysen) is a model covering the area of the Aysén Fjord. It is also barotropic, but aside from 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 and Campuzano (in press).

The third level, Chacabuco, covered the inner area of the Aysén Fjord. It is a baroclinic model, with a cartesian geometry of 11 vertical layers. Its resolution is approximately of 100 m, and it was over this level that the lagrangian particle-tracking sub-model was implemented. The numerical grid was generated using bathymetric data from Armada de Chile (Chilean Navy), using geo-statistic methods in order to generate a smooth bathymetry in areas where the point coverage was not accurate enough.

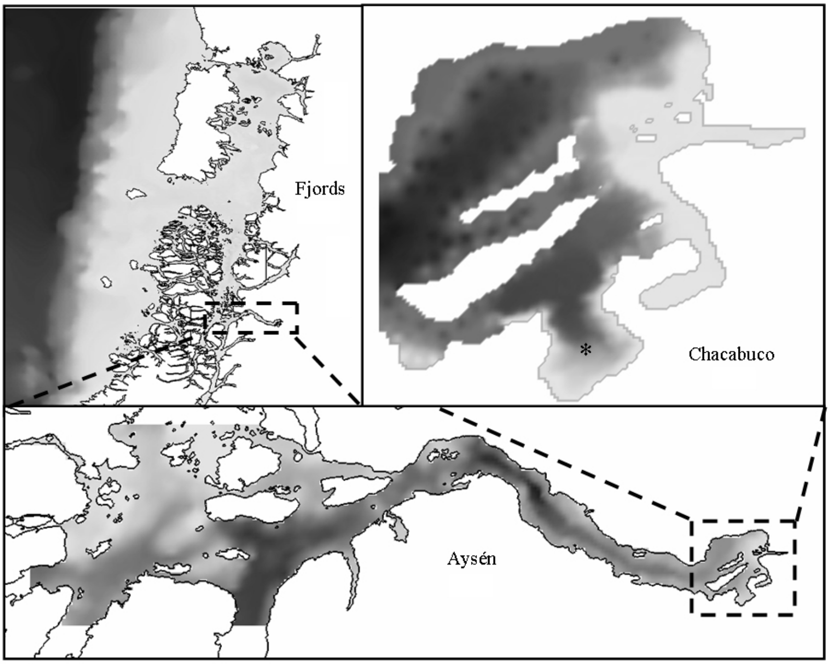

FIGURE 1: *Geographic area covered by the 3 level nested modeling structure in southern Chile. Grayscale areas represent each of the model grids. Chacabuco bay, where the particle-tracking model was mounted, is marked with an asterisk.*

The three models were initialized for 10 days with the purpose of stabilizing Aysen's Fjord water level, followed by a 25 days run to initialize water properties (temperature and salinity). Finally, with tide signal, temperature and salinity stabilized, a third 16-day run was implemented to simulate pellets dispersion in the bay area. Table 1 shows the main characteristics of each of the three models.

3.2 Lagrangian Particle Tracking Module

In what follows we describe the parameterization and assumptions used in relation to salmon farming loads and their dispersal in the water column.

Discharge volume: A fish density of 10 kg m^{-3}, for every 6000 m^{-3} cage, was considered for pellets output with a food/biomass ratio of 1.2. Only 5% of this load was considered to pass cage's depth and fall through the water column. We have further assumed that half of these wasted pellets were eaten by local marine fauna (Cromey et al. 2002). This pellet mass (in Kg) was then converted to particles assuming a caliber 2500 pellet (0.9 g per pellet, taken from Ewos Chile website, `http://www.ewos.com/cl/`, visited on 07/23/2007). The final number of particles was calculated as 450 particles per cage every two hours.

Sedimentation Velocity: Previous work has shown that sedimentation velocity depends on particle size (Perez et al. 2002) and that pellets suffer changes in their size as they descend through the water column (Chen et al. 1999). Here we have simplified this process applying a constant sedimentation velocity. The main purpose of this simplification was reducing calculation time and hardware requirements, given the rather large number of particles tracked in our simulation ($> 10^9$).

Salmon Production Cycle: Salmon farming involves different fish densities for each stage of the production cycle. For the purposes of this model we chose a fixed density (10 kg m^{-3}) corresponding to a high production stage. We subsequently tracked their discharges every 2 hours.

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

3.3 Sensitivity Analysis

Sensitivity analysis was done defining default values for every parameter tested (default run), and then adjusting them within the range found in literature to create sensitivity scenarios (Cromey et al. 2002, Panchang et al. 1997, Perez et al. 2002, Chen et al. 1999, Wiberg 2004). Seven scenarios were defined as shown in Table 2. The variable over which we perform the sensitivity test was the number of particles on day sixteen of simulation (N_{16}) in a specified area. The area was chosen after sampling the model for number of particles in a series of boxes over the whole bay. We chose the one showing greater variation between sensitivity scenarios. Model sensitivity (Sx) was evaluated as the change in "N_{16}" relative to changes in a model parameter "P" (Huntley et al. 1987), using equation (1).

$$Sx = \frac{(N_{16s,x} - N_{16def})/N_{16def}}{(P_{s,x} - P_{def})/P_{def}} \tag{1}$$

Where $N_{16s,x}$ is the value for N_{16} for the *x* scenario in the sensitivity analysis, and N_{16def} is the value for N_{16} on the default run. $P_{s,x}$ correspond to the value of parameter P for a given sensitivity scenario *x*, while N_{def} is the default value of the parameter.

3.4 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 were added to show pellets dispersal, relevant hydrodynamic data and GIS coverage. 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 its usage and to fulfill their information requirements.

4 RESULTS

The Chacabuco hydrodynamic model was validated with respect to salinity and water level. The model is capable of reproducing the typical halocline of the Aysen fjord, with the river flowing seaward through the upper level of the water column (Fig. 2). When comparing water levels given by the model with real values taken from mareographic station located inside the model, the results shows a good fit, with an r^2 of 0.94 (Marin and Campuzano, in press). Thus, the model is able to simulate the main characteristics of the estuarine system in the Chacabuco bay area. Therefore, the validated model 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 (pellets dispersal after 16 days of simulation of five cages throwing 450 particles every 2 hour) is shown in Figure 3. The majority of the origins showed pellets dispersing mostly beneath the cages or in distances between 100 m and 500 m from the cage's center. The greater dispersal in our simulation reached 1100 m, not including isolated particles. In total, pellets covered between 17% and 27% of the Chacabuco bay area. Results for the sensitivity analysis, grouped by scenarios, are shown in Table 3. The most sensitive variables were those defining resuspension; specifically erosion and deposition shear stress. The management tool was delivered to local decision makers. Additionally, there is an online version of the tool (mapserver format: `http://ecosistemas.uchile.cl/ecomanage/resultados`). The tool has already been used in the process of generating new environmental regulations for the Aysen region (DGA, CONAMA, personal communication).

5 COMPARISON WITH OTHER MODELS

We have shown the development of a lagrangian particle tracking model that can be used by salmon farmers and local decision makers. When comparing model's output with previous work with lagrangian approaches (Cromey et al. 2002, Cromey and Black 2005), the results are qualitatively similar. DEPOMOD is the only model with its dispersion module validated, showing between 13% and 22% of difference between modeled and observed values (Cromey et al. 2002). Thus, we have used it as a reference in this comparison.

There are some important differences between MOHID and DEPOMOD that should be taken into account before comparing them. First, MOHID sedimentation velocity was fixed during the whole simulation (1.28×10^{-1} m s^{-1}), while DEPOMOD uses random generated rates taken from a given range of values. The amount of particles simulated with MOHID (4×10^9) is five orders of magnitude above DEPOMOD (7×10^4). In fact, our volumes were close to real production values for particulate wastes discharges from Chilean salmon cages (EIA reports from salmon farmers POCH, 2004). Another important difference is the spatial and time scale of both models. While Cromey et al. (2002) used a grid definition of 10x10 m, covering an area of 0.25 km^2, here we used a grid of 100x100 m, covering an area of 147 km^2.

TABLE 1: *Main properties of the 3 nested model system.*

Model	Nesting Level	Grid Definition (km)	Geometry	Type	Discharges	Tides
Fjord	1	2.2	Sigma, 1 layer	Barotropic	No	FES2004
Aysén	2	0.5	Cartesian, 1 layer	Barotropic	Yes	Fjord Model
Chacabuco	3	0.1	Cartesian, 11 layers	Baroclinic	Yes	Aysén Model

TABLE 2: *Default values and sensitivity analysis scenarios. For every scenario, defaults parameters were modified to fit a range of values founded in literature.*

Parameters	Default values	**Resuspension**			**Sedimentation**		**Random movement**	
		E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**
VARVELHX*	**0.02**	-	-		-	-	0.04	0.01
VARVELH*	**0.02**	-	-		-	-	0.04	0.01
Critical Shear Stress of Erosion	**0.02**	0.01	0.04	1×10^{-5}	-	-	-	-
Critical Shear Stress of Deposition	**0.004**	0.002	0.008	1×10^{-5}	-	-	-	-
Erosion Rate	**0.005**	0.0025	0.01	1×10^{-10}	-	-	-	-
Sedimentation velocity	**0.128**	-	-		0.096	0.064	-	-

*varvelhx y varvelh are both model parameters determining particle random movement

TABLE 3: *Results from the sensitivity analysis. Each scenario is represented by the relative amount of variation of a given parameter from their default values. Sensitivity was calculated based on Huntley (1986).*

Sensitivity Scenario	Sensitivity (x 10^3) as particle number			
	200%	**-75%**	**-50%**	**-200000%**
Resuspension (E 1-3)	-664.3		335.5	982.8
Sedimentation Velocity (E 4-5)		-1.8	107.1	
Random Movement (E 6-7)	90.5		128.6	

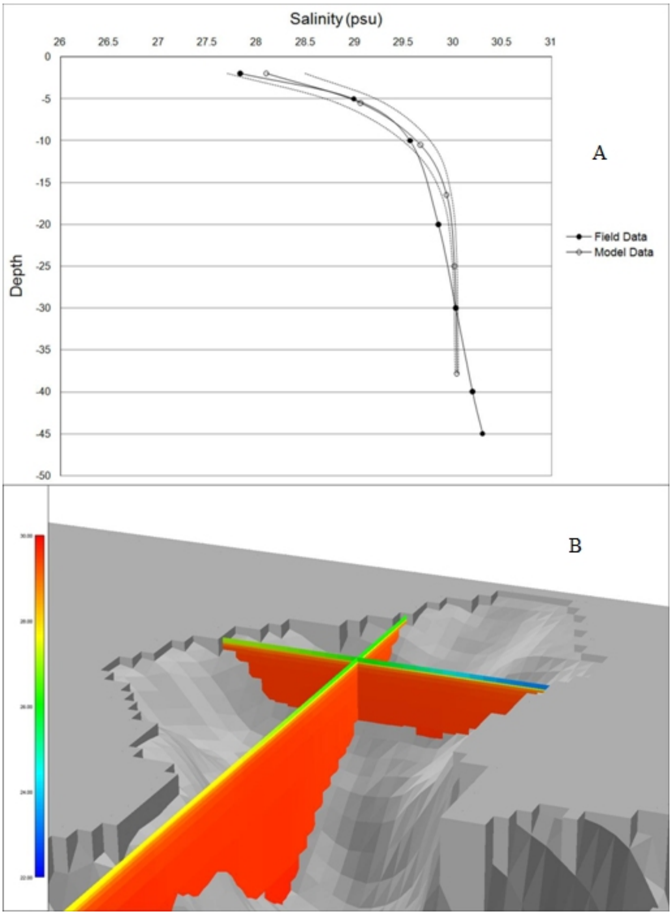

FIGURE 2: *Salinity values for model results (○) and available field data (●). The dotted lines represent standard deviation of model results.*

The time span of both simulations is also very different. Our model ran for sixteen days, with particle discharges every two hours for five origins, while Cromey et al. (2002) shows a 24 hour simulation with a single discharge. Despite the differences just mentioned, DEPOMOD and MOHID show similar results in their pellets' dispersal simulation. Cromey et al. (2002) showed that pellets dispersal occurred mainly beneath the cages (0-100 m), reaching a maximum distance for pellets dispersal of 200-300 m from the cage center. Our results, for comparable depths, show the same pattern, but with maximum dispersal distances of 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 (Cromey et al. 2002) and in general, with previous simulations of particulate waste dispersal (Corner et al. 2006, Panchang et al. 1997, Perez et al. 2002).

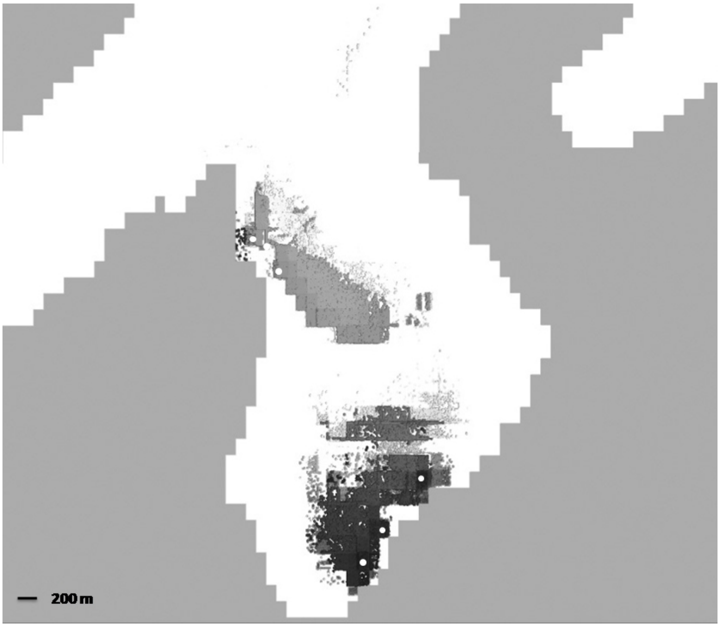

FIGURE 3: *Final spatial distribution of our 16-days simulation. Darker particles represent the results from the default simulation, while grayscale particles symbolize particle dispersion from the sensitivity scenarios. White circles shows each cage location.*

6 A BROADER CONTEXT

Models, like the one we have developed here, do not gain enough relevance until they are consider as part of a wider strategy, thus allowing the application of their results outside academic circles. A management framework we think is able to provide this wider context is Integrated Coastal Zone Management (ICZM; Turner 1999, 2000) is one strategy where models can be used. This management framework understand the relationship between nature and society as a process where perturbations generated from the former alter some ecosystem functions, eventually affecting the flux of ecosystem services to society, generating negative impacts over it, in a cycle called Driver-Pressure-State-Impact-Response. ICZM also provides a good support for stakeholder involvement in any of the multiple stages of project development (Christie et al. 2005, de Araujo et al. 1999).

In this work we understand stakeholders involvement as a continuum from partial involvement, or cooperative research (e.g. information exchange agreements), to collaborative research, where scientist and stakeholders jointly develop research projects. In any point of this spectrum, recent studies show that participatory research is able to contribute to scientists and stakeholders more informed about each other and better engaged in projects' objectives and outcomes (Hartley et al. 2006). Furthermore, stakeholder involvement has the potential to increase their self-reliance and awareness of the issues being investigated, facilitating more equitable trade-offs between stakeholders with competing interests (de Araujo et al. 1999). From this point of view, our experience during the development of this work showed that stakeholders' involvement in the research process brings a series of benefits: (1) Considering the large field data required to set model's initial/boundaries conditions and for the validation process, government stakeholders participation -and their data bases- were a key element in the data gathering period, (2) the working relationship generated with local stakeholders allowed us 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 et al. 2005) and (3) the creation and definition of modeling scenarios was facilitated during this interaction, linking research objectives with stakeholders' specific interests (Hanson et al. 2006).

However, there's a huge distance between the theory and practice of ICZM, especially in the context of developing countries. ICZM requires an integrated approach to natural resource management, and strong institutions able to guarantee an equitable distribution of projects benefits among stakeholders, with the ability to resolve conflicts between partners, supervising the realization of conflict-solving agreements and assuring stakeholders participation (Oracion et al. 2005, Pollnac and Pomeroy 2005). None of these conditions are satisfied in Chile. First of all, Garces (2005) proposes that Integrated Management (IM) would not be possible given the reductionist approach taken by Chilean environmental institutions and legal framework. Furthermore, Chilean economic orthodoxy, based on a neoliberal economy with small-state, free-market priorities, sustained on raw material exports, privileges economic growth -measured as GDP increase- over other aspects of economic welfare, even showing a hostile attitude over more sustainable initiatives (Carruthers 2001).

On a potential scenario of ICZM, this historical predilection towards the generators of this economic growth on a national level (private companies, multinationals, sometimes the government itself) (Saez and Cerda 2007) over other more sustainable aspects has produced uneven relationships between stakeholders on the local (regional) and central (national) level, limiting government institution's capacity to solve potential conflicts. Finally, participatory processes are seriously constrained, mostly explained by; (1) stakeholder's apathy towards participatory measures and proceeding given recent historical and political developments (Carruthers 2001) and (2) a fragmentary, merely informative "top-down" approach by government institutions towards stakeholders participation (Bachmann 2007, Fraser et al. 2006). It's under this socio-political context that this work was meant to improve local decision-making processes involving salmon farming particulate waste management, strengthening regional environmental institutions. In the context of a developing country like Chile, we expect this to be one step towards ICZM.

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