Numerical modeling of aquaculture: A multiscale task

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Abstract. *Fish farming activities are a relevant economic resource in coastal waters, which have grown in a significant way in recent decades, often with deleterious environmental effects [1]. The sustainability of the activity requires proper management and especially an appropriate site selection, which avoids use conflicts and considers adequately the potential effects before they occur. For this purpose numerical modeling is a key tool for a sustainable aquaculture.*

Aquaculture is a complex activity that has environmental effects at different scales and influences and it is also influenced by the surrounding environment. Therefore the correct modeling of the activity must consider the different scales at which the aquaculture could influence, as well as the effect of environment on the activity and the interference of cultured fish over themselves.

This work describes the application of a modeling protocol to assessing the carrying capacity of fish culture in marine waters. It is a sequential process which considers the critical condition for environmental factors and culture characteristics. This procedure is applied to adequate areas for marine aquaculture development after a GIS selection process.

Keywords: *Marine aquaculture, Carrying Capacity, Environmental Impact, Coastal Management, Modeling*

I. INTRODUCTION

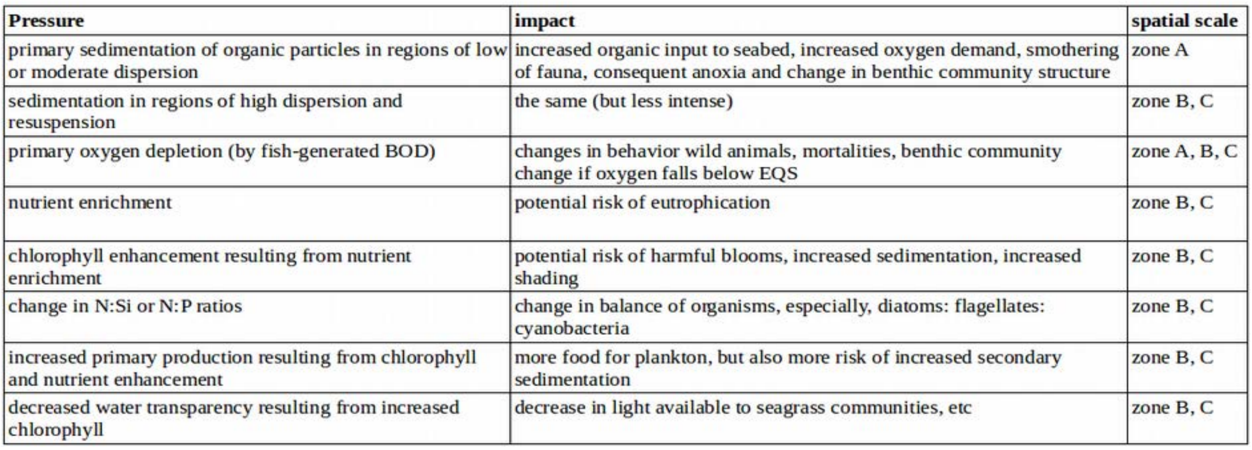
Worldwide the increasing demand for fish protein over the last decades has led to a significant intensification of aquaculture production. This aquaculture intensification resulted in a deterioration of coastal marine systems and their living resources in many cases [2]. Disturbance effects of fish farming on the seabed are quite well known for salmonids [3, 4, 5, 6, 7] as well as for the Mediterranean sea bream and sea bass farming industry [8, 9, 10]. Basically, sedimentation of food particles and faecal pellets under and around fish pens and cages negatively affects the biogeochemistry of benthic communities [11]. These effects on benthic environment are in general quite similar to the empirical model of macrobenthic succession along gradients of organic enrichment described by Pearson and Rosenberg [12].

Regarding cage aquaculture disturbance on water column, the real, perceived and potential effects are related to nutrient enrichment from excretory products and waste feed near cages [13, 14, 4]. Pollution problems have the potential to lead to oxygen depletion, ammonia toxicity and algae growth (i.e. eutrophication). These effects are most severe in shallow or confined water bodies [6], with poor water renewal, vertically stratified, and with nutrient input from non-aquaculture sources; they also tend to be serious in regions where intensive aquaculture systems are concentrated. In such areas, nitrogen wastes (for example, ammonia and nitrite) that exceed the assimilative capacity of receiving waters lead to deterioration in water quality that is toxic to fish. In most of situations, the increase in nutrients produced by the aquaculture in the vicinity of the facility does not produce a detectable rise in chlorophyll concentration. This decoupling is attributed to the high levels of water removal on the open sea, which means that phytoplankton is not in contact with the nutrients time enough to produce significant increase in their biomass [15].

The Carrying Capacity evaluation related to marine farming is imperative in the context of sustainable aquaculture [16]. According to the terminology proposed by the [17], Productive Carrying Capacity (PCC) evaluates from the point of view of the viability and welfare of the culture and Environmental Carrying Capacity (ECC) is the ability of the medium to assume the impact of the activity.

One of the key issues in the context of the ECC, is the understanding of the impacts of aquaculture and the identification of the scale on which they appear. The scale issues in fish farming environmental effects have been considered by Silvert [18], Gyllenhammar and Håkanson [19] and Tett *et al*. [20]. Although the waste input from a

Table 1. Ecological pressures generated by the aquaculture in floating cages, and consequent impacts on ecosystems [20]



Pressure	**impact**	**spatial scale**
primary sedimentation of organic particles in regions of low or moderate dispersion	increased organic input to seabed, increased oxygen demand, smothering of fauna, consequent anoxia and change in benthic community structure	zone A
sedimentation in regions of high dispersion and resuspension	the same (but less intense)	zone B, C
primary oxygen depletion (by fish-generated BOD)	changes in behavior wild animals, mortalities, benthic community change if oxygen falls below EQS	zone A, B, C
nutrient enrichment	potential risk of eutrophication	zone B, C
chlorophyll enhancement resulting from nutrient enrichment	potential risk of harmful blooms, increased sedimentation, increased shading	zone B, C
change in N:Si or N:P ratios	change in balance of organisms, especially, diatoms: flagellates: cyanobacteria	zone B, C
increased primary production resulting from chlorophyll and nutrient enhancement	more food for plankton, but also more risk of increased secondary sedimentation	zone B, C
decreased water transparency resulting from increased chlorophyll	decrease in light available to seagrass communities, etc	zone B, C

single fish farm can be treated as a point source, some of it may contribute to ecological pressures at a distance from the source. It is thus important to consider the spatial extent of the ecological pressure and its impact (Table 1).

Although these depend on both farming method and local environmental conditions. Three zones around a polluting point source can be distinguished:

- Immediate vicinity (Zone A: meters to hundred meters): dissolved substances and free buoyant particles remain in this zone for only a few hours, and most sinking particles (including food, faeces and dead fish) reach the seabed here and can produce increased organic input to seabed, increased oxygen demand, smothering of fauna, consequent anoxia and change in benthic community structure.
- Local scale (Zone B: hundred meters to kilometers): dissolved nutrients (and other dissolved substances produced by farms) spread through and remain in this zone for a few days, giving rise to long-term increases in mean concentration, and the residence time allows phytoplankton biomass to increase significantly if light is adequate.
- Regional scale (Zone C: many kilometers), with water residence times of weeks to months, often spatially heterogeneous (e.g. with mixed, frontal and stratified waters), and only impacted by the aggregate output of large sources of pollutants; also important because it provides the 'farfield' conditions against which zone B changes should be considered.

The spatial scale of the areas described (A, B and C) is variable. It depends on the topographic and hydrographic characteristics of each site, the ability of different pollutants to spread and to interact with the different components of the environment (physical and / or biotic), the nature of sediments or the water column, the nature and mobility of affected populations and biocenosis, and the interaction with other human activities or natural processes.

Thus ECC analysis should be performed on the three spatial scales mentioned above. For PCC the scenarios should be related to different culture scales (cultured biomasses, cage sizes and its spatial configurations).

One of the hardest parts of understanding and modeling the environmental impacts of aquaculture is identifying and quantifying secondary effects [21] and to predict whether these will be undesirable. An undesirable disturbance could, quite simply, be any unwanted event, such as the pollution of a beach by unpleasant foam derived from excessively abundant micro-algae [22]. It could, fundamentally, be any significant change in the structure or function of marine ecosystems, especially those changes that damage sustainability for human use or impact on species or habitats identified for conservation [22]. One possible concern in the determination of what impacts are acceptable is the prospect of recovery - is the impact reversible or not? [21].

II. METHODS

The procedure is applied on water masses of selected sites as a result of the use of GIS technologies. The carrying capacity is evaluated sequentially, based on the predictions of different environmental scenarios. When the analysis requires it, the simulation scenarios are nested at different levels of spatial resolution:

- A first analysis of the rate of water renewal establishes the productive capacity of the area. For this purpose simple models like the perfect mix proposed by Silvert [21] or, in more complicated cases (long or irregular coastal stretches), hydrodynamic models [23] may be used. In this simulation we used a variable linked to water quality such as nitrates. The water mass in which the facilities are placed should have a "good ecological status", not reaching the limiting values established by the Framework Directive.
- Subsequently the assimilative capacity of the benthos is determined by means of sedimentation rates of particulate waste from aquaculture. Naturally benthos is able to assimilate certain amount of organic matter by microbial degradation processes, both aerobic (nitrifying) and anaerobic (denitrification). The sum of these processes establishes the "carrying capacity". In a nutshell, using the model of accumulation-degradation as proposed in [24], in which the accumulation and degradation processes equals at equilibrium, it can be determined the rate of sedimentation, which is used as limiting value. The sedimentation rate can be calculated for each situation of culture using simple equations [25] or using more or less complicated Lagrangian dispersion models (DEPOMOD, MOHID).
- A second dispersion simulation analyzes different possibilities of grouping cages in production units and determines the number, spacing and distribution of cages for an optimal grouping. The criteria used in this case are the risk of hypoxia in the culture [26] and toxicity by the discharge of ammonia [27] or the occurrence of diseases and stress in farmed fish [28]. The analysis of the influence of both variables under various scenarios of cage grouping is determined by a dispersion model, preferably coupled to a water quality model.
- Finally a hydrodynamic and ecological model analyzes a realistic case of facilities distribution. At this point we have determined the areas of aquaculture interest, the allowable tons of culture, both for farmed fish health and environmental sustainability, the location of possible concessions and the optimal distribution of cages within the facility. Now we are able to offer one or more solutions (particular distribution of facilities) compatible with the above results. We should verify that the proposed solutions are fully compatible with the environment and other existing activities. This verification should be based on a dispersion model that adequately consider the hydrodynamic and ecological variability (benthic and water column). It also should be able to simultaneously consider all sources and types of existing spills in the area (cages, emissary, rivers, etc.). Finally, it should protect environmental values. Therefore, complex modelling systems are required (MOHID, COHERENS, POM, MIKE3D, Delft, etc.).

Extreme environmental conditions were simulated. Those which produce most damage to the environment when a culture is simulated in the situation of maximum production.

III. DISCUSSION AND CONCLUSIONS

Evaluation of Carrying Capacity is an analysis often postponed to later phases of Site Selection for aquaculture. Various international forums advocate the inclusion in the processes of Site Selection of such studies in order to develop an ecosystem approach [26].

Simulation models are so powerful that provide an excellent opportunity to apply this kind of approach. The protocol developed here uses several of them and is an ideal framework for this type of study. It is a sequential approach that follows a scheme that progressively applies various criteria by an increasingly restrictive and complex order. Thus allowing the reserve of the most complicated tasks (hydrodynamic simulations, 3D dispersion studies) for more specific scenarios (suitable area, number of cages, type, depth, etc.) and avoiding also the need to perform a considerable number of alternatives. The use of extreme conditions in simulations ensures a huge margin of security to use model predictions on aquaculture management. According to the results for the two first steps, size, depthR. and fish density of a cage culture are sized for each facility. The third step modifies the internal organization of cages within a facility to accomplish culture welfare. The last model takes into account interactions with other sources of discharge and its impact on the environment at different nested scales.

The water column parameters related to dissolved discharge are appropriate for the analysis of the global ECC of a zone of interest for aquaculture development, as well as to evaluate interactions between cages and concessions. Its effects appear not only in the vicinity of the cages but at greater distances (see Table 1). In addition, synergistic effects can be evaluated on these variables. The main obstacle to this approach is the absence of quality objectives or tolerable degree of disturbance legally established. The Water Framework Directive is an exception to fixing precise quality limits to the water column parameters, however it is not fully implemented for some factors, especially for numerous biological communities.

The greatest impact of cages comes from the particulate discharge (feed and faeces), and, usually, is restricted to a few hundred meters (See Table 1) around the installation [29]. The capacity of the benthos to assimilate the impact of aquaculture has been evaluated by means of the rate of sedimentation acceptable. So, location and design of individual cages is defined through the environmental and technical variables determining the sedimentation rates. Modeling to set minimum distances between concessions cages is usually enough to avoid a synergy in the footprint of organic matter on the benthos, but not to control the impact on each cage individually. According to dispersion models the losses of feed not consumed (overeating) are primarily responsible for the impact on the benthos [30, 31]. Only good practices on management of the facilities could control individual impact of every cage; that is to say, it only suffices a single cage badly managed to produce an undesirable perturbation, although this on a very localized scale.

The great adaptability of the methodology used in this work, applicable to any system of cultivation and farmed species, make it a very useful tool in management (fish density, distance from the cage, cage diameter, etc.) and planning (limit of production, appropriate sites, etc.). In addition it is a very versatile protocol that can be adapted to other legal frameworks and consequently to other geographical areas; it also allows the use of different models (hydrodynamic, mixing, etc.), as well as introducing or varying the criteria for protection of natural heritage and animal welfare.

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