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A Modelling Approach to Estimate the Environmental and Productive Carrying Capacity for a Mediterranean Coastal Marine Culture Park

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Abstract

Fish farming activities are a relevant economic coastal resource in the warm oligotrophic Mediterranean waters. This work describes the application of a numerical model to determine the carrying capacity of a mixed gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) culture in a Marine Culture Park, located in the coast of the Region of Murcia (SE Spain). The MOHID modelling system was used to simulate the hydrodynamics and ecological conditions of the study area, and to address the processes related to fish farming activities such as pellet deposition of different sizes, nutrient recycling and oxygen consumption.

The productive carrying capacity (PCC) and the environmental carrying capacity (ECC) were evaluated under different production scenarios with critical values for the culture and the environment. The selected indicators to assess PCC were the toxic level of ammonia species and the dissolved oxygen concentrations necessary for cultured fish survival. The ECC was assessed by means of eutrophic levels both in the sediment and the water column and the tolerance of benthic organisms to organic matter sedimentation.

Results led to the definition of the minimum distances between installations, so to minimize their negative interactions, and to the quantification of the influence of dissolved and particulate products on the production. Finally, it was evaluated the capacity of the aquatic system to maintain the simulated biomass without undesirable environmental disturbance.

The methodology employed in this work can be adapted to any system and cultured species, thus providing significant support to management decisions regarding the intensity of fish farming activities.

Keywords: Aquaculture; Anthropogenic impacts; Carrying capacity; Coastal zone management; Mohid model; Water quality modeling

Abbreviations: AZE: Allowable Zone of Effect; DON: Dissolved Organic Nitrogen; DOP: Dissolved Organic Phosphorus; ECC: Ecological Carrying Capacity; MCP: Marine Culture Park; NPZD: Nutrient Phytoplankton Zooplankton Detritus Biological Module; PCC: Production Carrying Capacity; PhCC: Physical Carrying Capacity; POM: Particulate Organic Matter; PON1-5: Particulate Organic Nitrogen pools; POP1-5: Particulate Organic Phosphorus Pools

Introduction

Worldwide increasing demand for fish protein over the last decades has led to a significant intensification of aquaculture production, frequently with deleterious environmental effects [1]. Coastal areas have been the preferred locations for fish farming, mostly due to their hydrodynamic and ecological characteristics. The aquaculture activities intensification has, in many cases, resulted in an overall deterioration of the marine coastal systems and their living resources [2].

Mariculture production in the Region of Murcia (SE Spain) has grown since the mid 90's, from over half a ton to 10,000 tons of fish, and currently ranks among the top offshore aquaculture producers in Spain. One of the main areas of aquaculture development is the Polígono de Cultivo Marinos de San Pedro (San Pedro Marine Culture Park, hereafter referred as MCP) located in the eastern coast of Murcia (Figure 1).

The San Pedro MCP is one of the largest open sea facilities dedicated to fish production in the Mediterranean Sea. Although several companies operate in the MCP, this area could be regarded as a single environmental and sanitary unit in management terms. The MCP includes seven administrative concessions authorized to produce annually around 7000 tons of Atlantic bluefin tuna (*Thunnus thynnus*), gilthead seabream (*Sparus aurata*, hereafter referred as seabream), European seabass (*Dicentrarchus labrax*, hereafter referred as seabass), and other species with a minor production.

To date, the facilities operation has not led to an environmental impact above permissible levels as shown by environmental monitoring programs [3]. Thus, according to the adaptive monitoring approach from Peran et al. in IUCN [4], a production increase in this area could be feasible.

This work describes a methodology for obtaining the production carrying capacity (PCC) and ecological carrying capacity (ECC) based on numerical modelling tools.

Material and Methods

Study area

The San Pedro MCP is located on the southeast coast of Spain,

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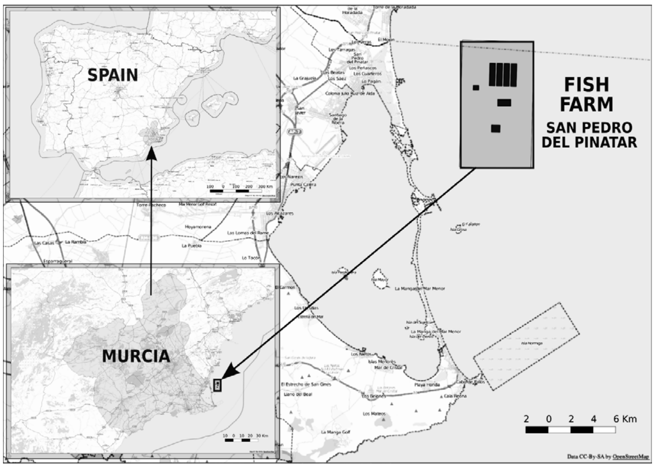

Figure 1: Location of the San Pedro MCP in south-eastern Spain.

in the municipality of San Pedro del Pinatar, off the eastern coast of Murcia. The MCP is located between 6.5 and 10 km off the coast and with depths ranging between 35 and 42 m (Figure 1).

This area is characterized by a wide continental shelf with a gentle slope that can extend off the coast as far as 35 km. The substrate under the production area is mostly occupied by soft bottom communities of biogenic sands and biogenic muddy sands. In this coastal area, Posidonia oceanica beds are present with a distribution limited to maximum depths around 25 and 30 m in the MCP northern and southern areas respectively. On average, the San Pedro MCP is located 1.5 km away from Posidonia oceanica beds. The oceanographic regime in the Murcian coast is highly variable. The area is located in the transition zone between waters flowing south from the Alghero-Provençal basin, with more Mediterranean characteristics, and the Alboran Sea waters under the influence of incoming waters from the Atlantic Ocean. In the outer continental shelf, the dominant flow regime depends on the main circulation patterns, while in the inner shelf wind exerts a much stronger control, giving rise to a highly variable local microcirculation [5].

Mediterranean planktonic communities resist eutrophication, not only due to the oligotrophic nature of the waters [6], but also to its trophic structure, where the "top down" control and the heterotrophs dominance over autotrophs play a key role [7]. Micro and mesozooplankton present the ability to feed directly from the detritus, preventing its nutrients to end up in the phytoplankton compartment and producing massive blooms [8]. Detritus is the second largest energy source after dissolved organic matter [9].

The Mohid model

The MOHID Water is an open source numerical model part of the MOHID Water Modelling System [10]. The core of the Mohid Water is a fully 3D hydrodynamic model coupled with different modules comprising water quality, atmosphere processes, discharges, oil dispersion, etc. MOHID is programmed in object-oriented ANSI FORTRAN 95 and is able to simulate Eulerian and Lagrangian flow fields. For the objectives of this study, the hydrodynamic module was simulated coupled with the Lagrangian module and the water quality module. In order to simulate the deposition of the several forms of particulate material in the installations surroundings some modifications were performed in the original code. Five particulate organic nitrogen and phosphorus pools (PON1-5 and POP1-5 respectively) with independent sinking rates were implemented to simulate the particulate organic discharge from the fish cages. The Water Quality module, a nutrient-phytoplankton-zooplankton-detritus (NPZD) model, allows the simulation of the nitrogen, phosphorus and oxygen cycles, both in the water column and bottom sediments. For this case, the module was adapted to allow Zooplankton to feed directly from the detritus compartment (PON_1 and POP_1 pools) according to Michaelis-Menten kinetics, without the inhibition of the remineralisation processes. Nitrogen and phosphorus cycles are represented in Figure 2.

A conceptual aquaculture waste production model

The "production unit" was defined to deal with multiples configurations of sea cages and production scenarios. This unit was based in a standard sea cage of 25 m diameter by 20 m deep, the most common cage dimensions for the culture of these species. For the San Pedro MCP application, the production unit consisted on an equally mixed seabream and seabass net-pen producing 100 tons of fish per year. Good management practices were assumed and uneaten feed was estimated as the 3% of the total feed delivered (A. Belmonte pers. comm).

A simple mass balance equation between food and excretory products was used to estimate global waste inputs [11]. A detailed characterization of different wastes forms (PON_{1-5} and POP_{1-5}, ammonia and lixiviated products), temporal evolution and influence of temperature was attained by means of a bioenergetic model for seabream and seabass [12]. Daily estimated waste and oxygen consumption was distributed at hourly scale according to Calderer [13]. Sinking rates for

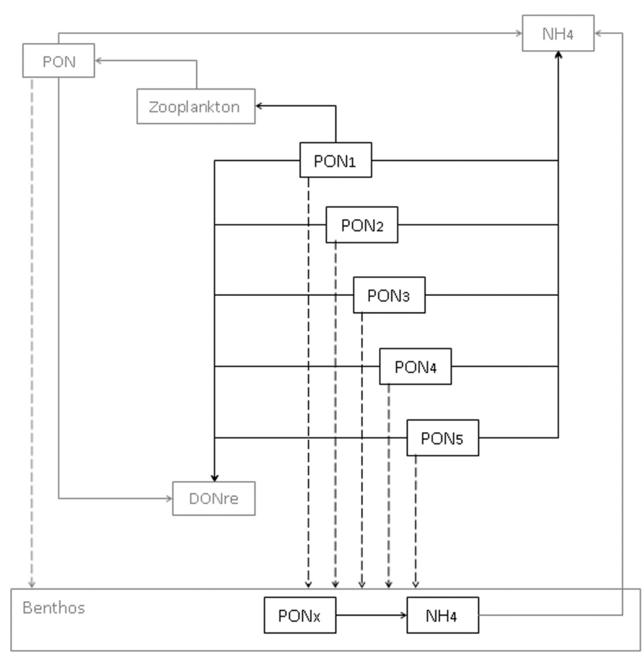

Figure 2: Scheme of the modelled nitrogen and phosphorus pools; for simplicity, only the nitrogen pools are represented. Arrows denote the processes that link the different components of the algorithm. The structure and processes from the basic setup of the Mohid Water Quality module are represented in dark gray, whereas the adapted processes for the POM pools simulation are represented in black. Sinking rate is represented by the dashed arrows. PONx stands for all PON pools.

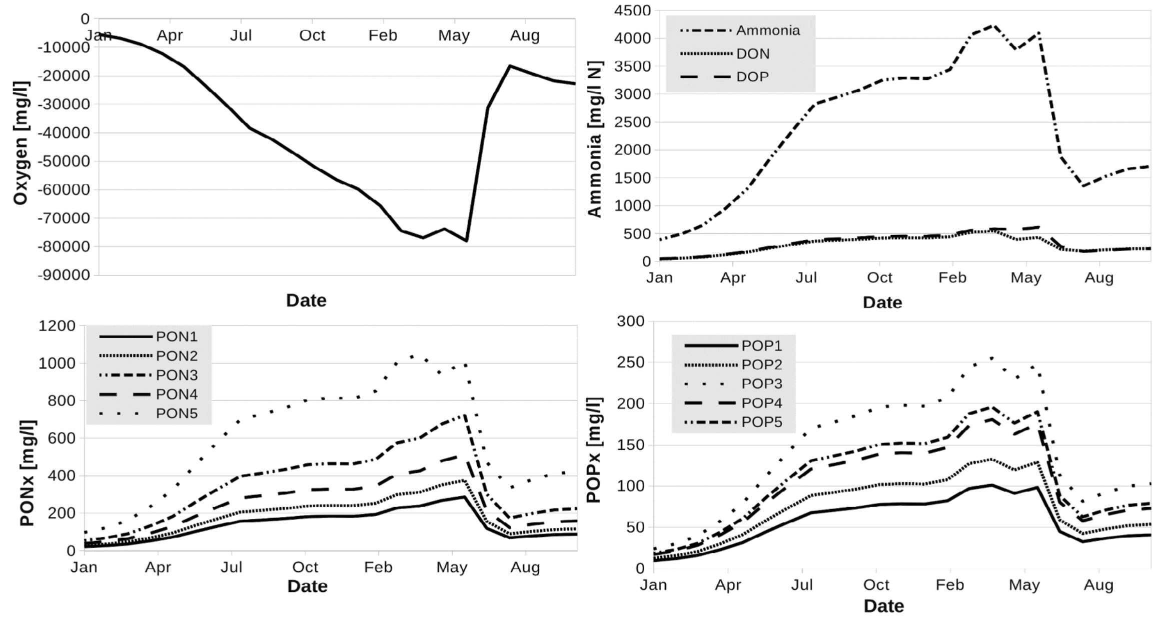

Figure 3: Complete cycle of oxygen consumption (top, left), dissolved nature releases (top, right), different organic nitrogen particles (bottom, left) and different organic phosphorus particles (bottom, right), for a mixed seabream and seabass culture used as input to simulate the different considered load scenarios.

Particle	Type	Sedimentation Velocity (m/s)	% Total Volume
PON_1 and POP_1	Detritus	0.00905	21.2
PON_2 and POP_2	Faeces	0.0246	18.6
PON_3 and POP_3	Faeces	0.0356	32.9
PON_4 and POP_4	Faeces	0.0463	22.1
PON_5 and POP_5	Unconsumed Feed	0.15	5.2

Table 1: POM Pools volumes and sedimentation velocities.

the different particle sizes were defined according to Magill et al. [14] (Table 1). A complete production cycle was modelled, considering it until commercial size for seabream and seabass was achieved (Figure 3). The dissolved by-products from aquaculture consisted in ammonia (NH_3), dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP). Oxygen is consumed during the organic matter remineralisation, though not represented in the diagram.

Following the precautionary principle the worst possible production scenario for the environment was considered for all the simulations. Thus, all the cages would operate simultaneously and had reached the maximum production of 100 tons per cage. In summary, the considered discharge corresponded to a 24 hour cycle for a production unit with 100 tons of stabled biomass at the end of its production cycle.

Carrying capacity modeling

In order to evaluate the effect of a production increase, the carrying capacity in the MCP was assessed according to the NIWA classification [15]. The selected indicators for aquaculture production were the Physical Carrying Capacity (PhCC), the Production Carrying Capacity (PCC) and the Ecological Carrying Capacity (ECC).

In this study area, and considering the benthic community cartography performed in the area [16], the PhCC was determined and aquaculture concessions should be placed in a depth range between 34 and 42 m deep. In spite of this limitation, the area fulfilling this requisite is large and allows the installation of a large number of production units in addition to those already authorized [3]. For that reason, in this study, we only focus on the PCC and ECC calculation.

The PCC corresponds to the maximum production from which adverse effects may occur on cultured organisms. The ECC corresponds to stocking or farm densities that cause unacceptable ecological impacts on water quality. PCC analysis was conducted under a hydrodynamic scenario comprising an area of 111 × 29 cells of 25 × 25 m with a constant depth of 40 m, and three layers (20 m, 16 m and 4 m). The model was forced using uniform currents covering three scenarios: calm currents 0.04 m/s; average currents 0.3 m/s and extreme currents 1 m/s. In all the scenarios, the simulation consisted in 60 production units aligned parallel to the current disposed in three sets of ten pairs of cages with a separation of 25 m between cages and of 50 m between rows (Figure 4).

In the ECC study, two nested domains were defined to obtain accurate local hydrodynamics. Level 1, or regional level, included a regular domain covering the entire Region of Murcia with a horizontal resolution of 886 m and Level 2, or San Pedro level, with a horizontal resolution of 246 m (Figure 5). The bathymetry used for obtaining both domains was the high-resolution digital terrain model of the Spanish Institute of Oceanography (IEO) [17]. The Level 1 was a 2-D application forced by the tides from the global tide model FES2004 [18] and its mission was to provide water levels to the nested Level 2. The Level 2 was a 3-D application with 10 sigma layers simulating hydrodynamics and water quality and forced by local wind data, from the nearby San Javier airport and environmental variables. The environmental concentrations used for model forcing were: temperature, salinity, oxygen, nitrate and phosphate climatological profiles, obtained for the study area from the World Ocean Atlas 2005 [19,20]. More details about the modelling configuration and validation can be found in [3].

In order to evaluate the ECC, both Eulerian and Lagrangian approaches were followed. In the Eulerian approach the hydrodynamic

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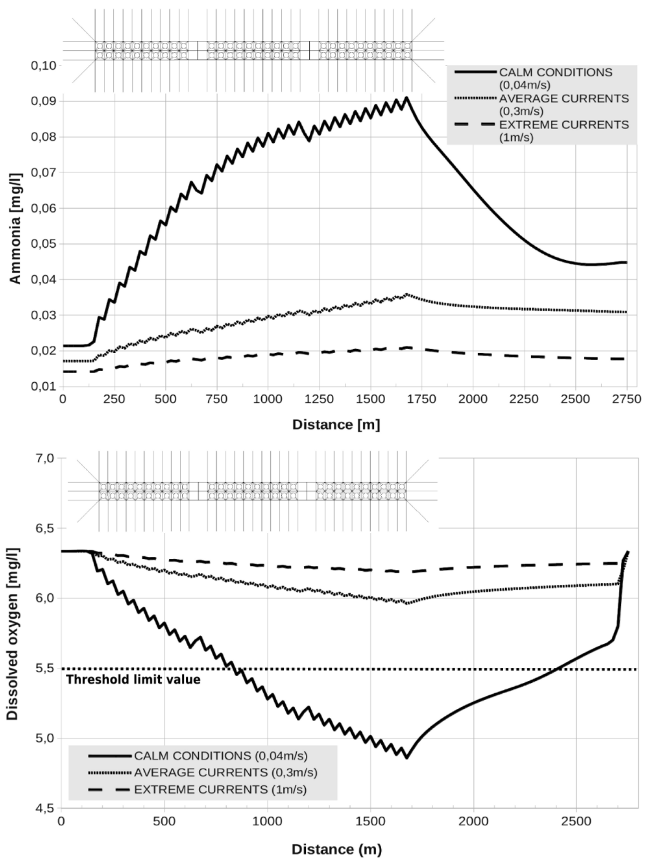

Figure 4: Ammonia (top) and oxygen (below) concentrations in the PCC simulation. Distance is measured from the beginning of the domain, the cage distribution is depicted on top of each figure. The oxygen threshold limit value is shown in the figure while the ammonia limiting value is out of the range of results.

and water quality calculus are obtained for each model cell and was employed to obtain the properties concentrations in the water column and benthos. In the Lagrangian approach allowed those calculi are performed for each Lagrangian particle and allow the accurate estimation of the cages footprint, as the particles are not limited by the model horizontal resolution.

Results

Production carrying capacity (PCC) modelling results

The selected indicators for obtaining the PCC were ammonia and oxygen. The species allowable limits for these variables provided simple guidance in terms of cage density and minimum distances between cages rows for the aquaculture facilities design.

Modelling results reveal an accumulative effect of ammonia between successive net-pens (Figure 4). Ammonia maximum modelled concentrations were obtained downstream to the 60 production units being 0.091 mg/l for calm conditions, 0.036 mg/l for average currents and 0.021 mg/l for extreme currents (Figure 4). These ammonia levels were below the fish deleterious interval between 0.2 and 2 mg NH_4/l [21].

In the case of oxygen concentrations, a minimum concentration for culture growth of 5.5 mg O_2/l was considered, value from which the ventilation frequency increases [13]. Modelling results show that oxygen values dropped along the production area, only reaching values below the considered limit during calm conditions (Figure 4). Stronger currents imply higher renewal rates in the water column, minimizing the decrease on dissolved oxygen partial pressure. From the results showed in Figure 4, it could be estimated that the maximum number of cages that could be grouped together with the described layout would be 24. From the twelfth pair of cages situations of stress might occur to the cultured fish. This curve could be used to obtain the minimum distance between installations. In the case of a group of 20 cages disposed in pairs with 100 ton capacity, a separation of 550 m would be necessary to ensure no negative effects due to low oxygen concentrations.

Basal ammonia concentration for the worst case scenario was not recovered in the simulated domain, whilst the oxygen concentrations recovered for all the hydrodynamic scenarios.

Environmental Carrying Capacity (ECC) modelling results

Taking into account the PCC results and the common practice of grouping cages in pairs, the proposed modelling scenarios consisted in two alternatives. The first alternative consist in 140 cages organised in groups of 20 cages with a fish biomass around 14,000 tons and an estimated annual production of 5,850 metric tons (Alternative I, Figure 6 Left) and a second alternative doubling the number of cages and thus the production and stabled biomass (Alternative II, Figure 6 Right). The Alternative I is similar in the distribution and has a slightly higher stabled biomass than the current MCP situation, though the current distribution was proven to be less efficient [22].

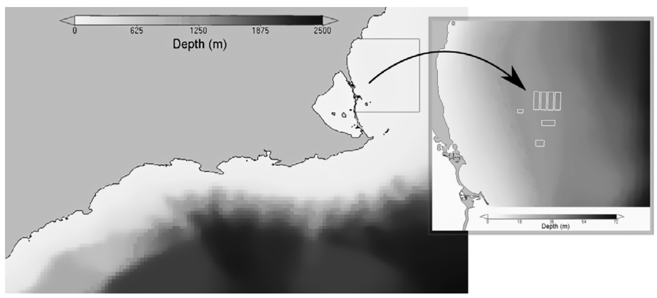

Figure 5: Bathymetry employed for the 2D hydrodynamic domain covering the coast of the Autonomous Community of Murcia. The red line limits the San Pedro nested domain. The white polygons mark the location of the MCP.

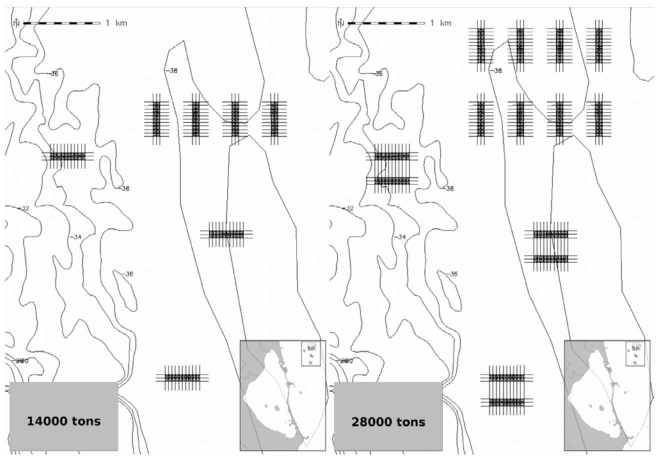

Figure 6: Carrying capacity study for San Pedro, alternative I (left) and II (right) description map.

The ECC was evaluated in terms of the eutrophication risk and the allowable benthos degradation. The selected indicators were nutrient and oxygen concentrations in the water column, organic matter discharge rate and organic matter percentage in the sediment.

Nutrient concentrations obtained for the two production alternatives were similar to those that observed in the environment with non-significant changes thus there should not be deleterious effects on the cultures and environment. The partial oxygen concentration in the water column decrease to minimum levels of 6.4 mg O_2/l within the installations. No cumulative or synergistic effects between facilities were observed with the two alternatives layout. Nor significant increments on nutrient levels and oxygen depletion were detected afar from the facilities, on water mass at regional scale.

The organic matter discharge rate integrates the five types of particles simulated and was converted to organic matter concentration per unit area and day. The organic matter percentage in the sediment includes besides the particulate material from the marine culture the natural organic matter from the natural processes. Therefore, it should be regarded as the organic matter concentration as commonly considered in monitoring plans.

Lagrangian modelling results allow to distinguish individual cage footprints. Maximum sedimentation rates of particulate organic matter (POM) were obtained immediately below the cages (3,500 mg $m^{-2}d^{-1}$) reducing rapidly from the cages location, approximately 40 times in 50 m. Footprints for the two scenarios were limited within 475 meters from the facilities (Figure 7 left).

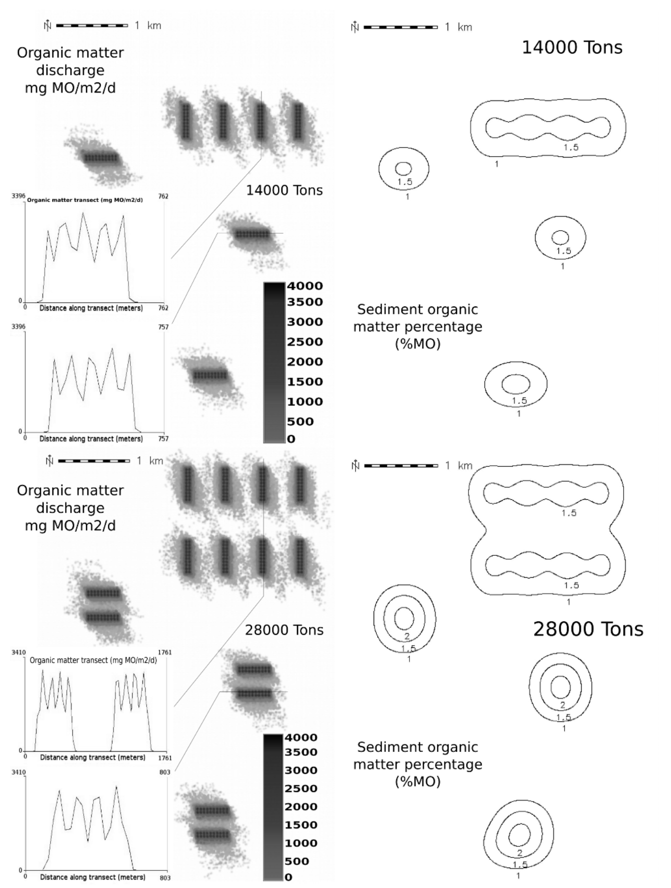

Figure 7: Modelled alternatives I (top) and II (bottom) for organic matter settlement (footprint) using Lagrangian tracers (left) and organic matter content in sediments using an Eulerian approach (right).

Results from the Eulerian approach provided organic matter percentage values in sediment (Figure 7 right). Alternative II presented an organic matter concentration in sediment of 2.2% while for the alternative I the modelled maximum was 1.7% a value slightly lower considering that the produced biomass is half the alternative II (Figure 7 right).

The organic matter accumulated in the bottom due to the fish faeces account only for approximately between 1 and 3%, while the rest of the organic matter comes from uneaten feed.

Discussion

Mathematical models have been frequently used for the last thirty years as a management tool in aquaculture. Initial applications consisted of simple dispersion models [11] without any regard to the hydrodynamics, and focusing on particulate materials accumulation impact on the benthos. Lagrangian models, i.e. DEPOMOD [23], soon were considered as adequate tools for the particulate discharges study due to its high spatial resolution. However, these models were limited since they were not able to simulate neither the hydrodynamic fields nor the biology of the water column. These limitations restricted their use to very local scale applications and to scenarios where impact due to soluble waste could be neglected. For these reasons, fully 3D hydrodynamic models as the Mohid Modelling System [10], which are able to simulate both the dissolved and particulate discharges and to represent heterogeneous hydrodynamic fields, were found suitable for this study purposes. The Mohid model includes, in addition to the Eulerian and Lagrangian dispersion modules, several modules than could resolve sediment biochemistry, nutrient-phytoplankton-zooplankton-detritus (NPZD) biological module, pathogen dispersion from fish faeces as faecal coliforms, floating oils derived from feed pellets, etc.

The water quality module incorporated in the MOHID model provides the total ammonia nitrogen concentration. Therefore this should be considered when interpreting the model results that the concentration values provided are higher than the concentration of the toxic form of ammonia. In any case, the observed total ammonia nitrogen concentrations ($[NH_4^+]+[NH_3]$) were lower than the lethal ammonia concentration (NH_3).

Dissolved oxygen concentrations could limit aquaculture production in aquatic environments, when the cultured fish respiration is such that lowers the oxygen concentration to a situation of chronic hypoxia. This situation could occur in extreme cases of calm hydrodynamic, high crop densities and/or closed cages. Dissolved oxygen concentrations would have to drop to values between 3 and 4 mg O_2/l to induce changes on fish motor activity while symptoms of anoxia usually occur at sublethal concentration of 1.5 mg O_2/l [13]. To set a conservative limit that ensures the absence of stress, it was considered the value of 5.5 mg O_2/l, beyond which the ventilation frequency increases [13].

Ammonia concentrations are larger the lower the flow velocity is, due to the greater cumulative effect resulting from the low water renewal. Stronger currents imply a greater turnover of the water column present on the installation that leads to a lower loss of dissolved oxygen partial pressure in the water column. In the calm conditions scenario (0.04 m/s) ammonia increase in a significant way, but do not reaches toxic levels (Figure 4, Top), and the oxygen concentration drops to within the limit considered critical for culture growth (5.5 mg/l), nearly shortly after the half of the second cages rows (Figure 4 Bottom). Both variables were found within security levels for culture in medium and extreme current situations. Current intensity also influences the recovery time of both variables between cages.

The design of the PCC simulations allowed setting a distance and density limit in the design of aquaculture facilities. The performed simulation causes the consecutively accumulation downstream of the cage discharges to the adjacent cages. From the modelling results, it could be estimated the maximum number of cages that could be placed on the same row. In Figure 6, the culture of twelfth pair of cages may be in situation of stress caused by the lack of dissolved oxygen in the water column. This curve could be used to calculate the minimum distance between installations, in this case it would be necessary a separation of 550 m to ensure no negative effects on the culture due to possible hypoxia situations.

Modelling results showed that for each alternative in the water quality of ECC simulations the limit concentration of 5.5 mg O_2/l was not reached. Regarding nitrogen, total ammonium nitrogen concentrations were always above the production limiting value of 0.2 mg NH_3/l. These results indicate that the limiting concentrations could be achieved in water tanks, with low water renewal, but in open water conditions nitrogen discharges would not limit production, as the hydrodynamic conditions and red-ox process would modify the toxic forms into harmless forms.

The main environment effect of aquaculture is generally observed on the benthos. In mesocosm experiments, a sedimentation rate of 1,500 mg C/m^2/d led to benthic community deterioration [24-27], but confined to the cages surroundings. Inside the facility, sedimentation rates range between 100 and 1,000 mg C/m^2/d^1, corresponding to the typical early stages enrichment of the Pearson-Rosenberg contamination model [28] could be detected. According to field experiments, Eleftheriou et al. [29] obtained that the addition of 2,100 mg C/m^2/d^1 favour wildlife and that altered conditions started at higher rates to 4,100 mg C/m^2/d^1, thus the impact of the simulated scenarios would be even lower (Figure 7 Right).

Sedimentation rates around 1500 mg C/m^2/d^1 would produce benthic community deterioration in mesocosm experiments [24,25]. Field experiments in East Mediterranean facilities [29] needed rates higher than 4,100 mg C/m^2/d^1 to obtain altered conditions. Our modelling results reached rates between 100 and 1,000 mg C/m^2/d^1, denoting enrichment.

The organic matter footprints are displayed in Figure 7 (left) with high graphic resolution due to the followed lagrangian approach. The discharge reaches the seabed and is shape is determined by the prevailing currents. The maximum peak was located beneath the production cages and that could lead to overlap due to cages concentration. The simulations allowed distinguishing each cage individual effect because its individual footprints have little interference between them. The graphic resolution of organic matter sediment content cannot distinguish individual cages, due to the relation of the eulerian approach to the model horizontal resolution. In spite that lower spatial accuracy, the obtained values are equally valid to identify potential environmental situations eutrophication.

The results of organic matter content in the San Pedro MCP showed values corresponding to submerged areas with external inputs [30], not very far of maximum natural values in the study area. None of the simulated alternatives reaches values over the environmental quality standards (<2% out of the Allowable Zone of Effect (AZE) and <4% within the AZE) established in Murcia [31].

Conclusion

Under the above assumptions and according to this study results, doubling the aquaculture activity would not produce any significant change out of the MCP. Inside the MCP, the areas beneath the cages could achieve early to moderate stages of contamination according to the Pearson-Rosenberg model [28]. It was also observed that the footprint was almost entirely due to the uneaten feed. Therefore, an efficient feeding management would reduce the unconsumed feed and would significantly improve the environmental compatibility. On the contrary, mismanagement would produce a severe impact on the bottom sediments and benthic communities.

From the modelling results, aligning more than 12 production units should not be a recommended practice, as low oxygen levels could appear in the water column that might result in fish stress. When considering groups of 10 production units, the minimum distance between groups to overcome potential hypoxia would be of 550 m. The cage diameter was set to 25 m, corresponding with the typical aquaculture installation at San Pedro MCP for other sizes the discussed results would not be directly extrapolated. Moreover, this distance is greater than footprint radio and would also avoid a synergic effect between facilities on the benthos. Finally, the implementation of the different organic matter pools related to the aquaculture production with Lagrangian tracers resulted in a complete tool that would aid managers in terms of aquaculture production and coastal management.

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