# Monitoring and simulating the operations and dissolved waste production of cobia fish farm off the coast of Cartagena, Colombia

## *Seguimiento y simulación de las actividades y la generación de residuos disueltos del cultivo piscícola de la especie cobia en la costa de Cartagena, Colombia*

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## Abstract

In 2008 the first fish farm in Colombia was constructed off Tierrabomba Island near Cartagena de Indias (10.3601 – 75.5966 NW). The farm was stocked with cobia, Rachycentron canadum. This species grows very rapidly, has high market value, and has been successfully cultured in the Caribbean. Three years after initial stocking of the cages, a study was begun to determine the farm's effect on the surrounding environment. Monthly physical variables and nutrients in the water column were measured for eight months at three stations located in proximity of the cages (5, 30, 100 m) and a control point (1000 m). At each station, samples were collected and measurements were made at depths of 7, 15 and 30 m. Additionally, a current Doppler profiler was installed near the site and data were collected continuously. This information was input and analyzed with the AquaModel fish farm simulation software (www.aquamodel.org). This software consists of a system of coupled sub-models of fish physiology, hydrodynamics, water quality, dispersion of dissolved and particulate wastes produced by the farm, and the ecological transformations of these wastes within the water column. AquaModel's 4-D simulation of farm operation and environmental impact is driven by the currents measured with the Doppler profiler as well as other field measurements such as water temperature, and the concentrations of oxygen, nutrients, and chlorophyll-a. The simulation indicated that the environmental impact of the farm was insignificant. Both the field measurements and simulation results show that there is rapid dilution of the total dissolved nitrogen downstream from the farm, and that the concentration of oxygen in the cages and in the ambient waters is above the 5 mg / L, more than sufficient to support rapid growth of the fish.

**KEYWORDS:** *Modeling, mariculture, Rachycentron canadum.*

## *Resumen*

*En 2008 se construyó la primer granja piscícola en Colombia en la isla de Tierrabomba cerca de Cartagena de Indias (10.3601 – 75.5966 NW). En el cultivo se sembró cobia (Rachycentron canadum). Esta especie crece muy rápidamente, tiene un alto valor en el mercado, y ha sido cultivada exitosamente en el Caribe. Tres años después de iniciar el cultivo, comenzó un estudio para determinar el impacto del cultivo sobre el ambiente circundante. Mensualmente, durante ocho meses se midieron las variables físicas y los nutrientes en la columna de agua en tres estaciones localizadas cerca de las jaulas (5, 30, 100 m) y un punto control (1000 m). En cada estación se colectaron muestras a las profundidades de 7, 15 y 30 m. Adicionalmente, se instaló un perfilador de corrientes Doppler cerca al cultivo y se colectaron los datos continuamente. Esta información fue ingresada y analizada con el Programa de Simulación para Cultivos Marinos AquaModel (www.aquamodel.org). Este programa comprende un sistema de submodelos para la fisiología del pez, la hidrodinámica, la calidad del agua, la dispersión de desechos disueltos y particulados, producidos por el cultivo, y las transformaciones ecológicas de estos desechos en la columna de agua. La simulación 4-D del AquaModel de la operación de la granja y el impacto ambiental es conducido por las corrientes que mide el perfilador Doppler así como por las mediciones en campo como son la temperatura del agua, y las concentraciones de oxígeno, nutrientes y clorofila a. Las tasas de crecimiento simuladas para el pez concordaron con los cambios temporales en el tamaño de los peces colectados en el campo. La simulación también indicó que el impacto ambiental del cultivo no fue significativo. Tanto las mediciones en campo como la simulación muestran que hay una rápida dilución del nitrógeno total disuelto en el gradiente horizontal, y que la concentración de oxígeno en las jaulas y en las aguas circundantes está por encima de los 5 mg/L, suficiente para sustentar el rápido crecimiento del pez.*

***PALABRAS CLAVE:*** *modelación, maricultura, Rachycentron canadum.*

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## Introduction

In recent years, knowledge of the biology of cobia *(Rachycentron canadum)* has increased given its more recent status as candidate for mariculture. The isometric growth of the species has been described in nature (Franks, Warren & Buchanan, 1999) and in culture conditions (Benetti, O'Hanlon, Rivera, Welch, Maxey & Orhun, 2010). Other studies have focused in its bioenergetics under static and fast swimming conditions for grow-out phase, and with variations of water temperature (Sun & Chen, 2014) (Rensel, Kiefer, O'Brien, Rust, Scott & Carter, 201). However, the environmental impact of offshore fish farming is still a matter of discussion worldwide. Environmental effects for offshore aquaculture have been estimated by in situ sampling and, more recently, by applying diverse models. Particularly, with mariculture development, many models have focused to integrate the mass balance equations with the hydrodynamic in culture site, with the aim to predict particulate and dissolved dispersion, and fish farm wastes deposition (San Diego-McGlone, Avanza, Villanoy & Jacinto, 2008) (Corner, Brooker, Teffer & Ross, 2006) (Cromey, Nickell & Black, 2002).

In 2008, the first mariculture project of the cobia species began in Colombia. As this was the first operation of this kind, ensuring the environmental sustainability of the project was of special importance. To map the predicted downstream concentration of nutrients, oxygen, and chlorophyll-a off the cages we ran simulations with AquaModel ® (Inc., Los Angeles CA, U.S.A.), an advanced model of farm operations and environmental impact that has been endorsed by the USA National Oceanic and Atmospheric Administration. This software has been successfully used to analyze proposed and operational farms of oysters in the United States, sea bass in Italy and salmon in Chile, among other countries. This model is a 4-dimensional (latitude, longitude, depth, and time) simulation of farm operations that runs within System Science Applications' EASy geographical information system. It simulates the growth and metabolic activity of the fish in cages, the associated production of dissolved and particulate wastes that are transported from the farm and the wastes biochemical transformations through the planktonic and benthic communities in the surrounding sediment and water column. Specifically, the model tracks the production, transport, and ecological fate of carbon, oxygen and nitrogen.

## Materials and methods

### Culture site

The cobia culture site comprised 4 ha in open water, with four nursery floating cages of 8 m in diameter and 9 m deep, with a capacity of 11 000 fingerlings by cage; and five grow-out floating cages 21 m diameter, 9 m deep with a capacity of 8800 fishes by cage. Cages were located 500 meters from shore at the NW side of Tierrabomba Island (10.3601 – 75.5966 NW), near Cartagena de Indias city (Figure 1). In the chosen site the average depth is 35 m, considering that the minimum value to be established is three times the cage height. This location is heavily influenced by El Dique channel, which drains water from the Magdalena River into Cartagena Bay. The volume flow rate within the channel ranges from 55 $m^3/s$ to 250 $m^3/s$ and carries an estimated sediment load of 822 $m^3/day$ (Olivero, *et al.,* 1997; Tuchkovenko, Lonin & Calero, 2002). The bottom type is muddy because the composition of the seabed in the culture site is mainly clay (86 %).

The Colombian coastal waters are influenced by the Inter Tropical Convergence Zone (ITCZ), and the weather is largely driven by the presence or absence of the Trade winds. There are three climatic regimes, named dry, transition and rainy seasons. During the dry season (December–March) the North and Northeast trade winds are strong, regular, and continuous; the transition season (April–July), is characterized by a high variability in wind direction, turning from north to south; while in the rainy season (August–November) the East-Southeast and Southeast winds are weak (Hydrographic and Oceanography

Research Centre – CIOH, 2005). Average temperature in the region is 27.7 °C, with maximum value of 31.9°C in August and minimum value of 26.5 °C in January.


**Figure 1.** Site location culture at the northwestern coast of Tierrabomba Island, Caribbean Sea (Modified from Universidad del Norte, 2003).

**Sampling procedures**

To assess the environmental effect of the farm, field data for the following variables were collected during eight months from May to December in 2011 .

- The concentration and spatial distribution of dissolved inorganic nitrogen (DIN).
- The vertical profile concentration of oxygen in the column water.
- Surface and bottom flow velocities.

Cage centers were registered with a GPS (Garmin, Kansas City MO, U.S.A.), and current's velocity was measured using an Acoustic Doppler Current Profiler (ADCP) (Nortek, San Marcos CA, U.S.A), installed on the seabed 25 m south of farm. The current database was extracted using the Surge software (Nortek AS, Rud, Norway) and displayed with WRPLOT View™ software (Lakes Environmental Software, Waterloo ON, Canada). Sampling stations were established at 5, 30 and 100 m downstream from the farm in the direction of dominant currents. A control station was also established 1 km downstream from the cages. At each of these stations, samples were collected at depths of 7, 15 and 30 m. Electronic charts of nautical and bathymetric information for Tierrabomba Island were obtained from the Marine and Coastal Research Institute – Invemar. Rainfall values during 2011 were obtained from the meteorological station of Hydrographic and Oceanography Research Centre – CIOH.

Water samples at each station were collected once a month with a 5-L Niskin sampler, placed in portable refrigerators, and carried to the laboratory where they were kept frozen at -20 °C. Water transparency was measured using a Sechii disk. Dissolved oxygen (DO) was measured with a digital

DO-meter (Model 556, YSI Incorporated, Yellow Springs OH, U.S.A), and salinity was measured with a refractometer and expressed as practical salinity units (PSU).

Monthly data from the cages included fish biomass, feed amount and frequency, and DO values inside the farm's cages. There were 3 types of cages according with the grow-out phase:

1) a nursery that contained fish that weighed between 2 g to 200g, 2) an intermediate grow-out cage that contained fish that weighed between 200 g to 1 kg, and 3) a final grow-out cage that contained fish that weighed between 1 kg to 4 kg. Cobia were fed pellets Nicovita Peces (40 – 45 % Protein, 7 – 15 % Fat) (Alicorp S.A.S., Callao, Peru). Pellets for each of the 3 cages were 4, 12 and 16 mm in diameter. The daily feed ration consisted of four meals at a feeding rate of 10 % biomass for the nursery fish, two meals at a feeding rate of 4 % biomass for the intermediate sized fish, and one meal at a feeding rate of 1-2 % biomass for the large fish. For each cage was sampled the weight of 100 fishes every 2 weeks to adjust the feeding ration. Hands feeders were used and this operation was monitored by divers to minimize losses

**Nutrient determination**

The nutrients concentrations in water samples were measured according to the Standard Methods. Dissolved reactive phosphorus was measured by persulfate digestion method and quantified by Vanadate Molybdate method, ammonium was measured colorimetrically by the phenate method, nitrate was measured in a UV spectrophotometer (Thermo Electron Corporation, Madison WI, U.S.A.) at 220 and 275 nm, and nitrite was measured with 1-Naftil, etilendiamide method and the optical density of the dye was recorded at 540 nm. Total suspended solids (TSS) was measured by filtering 2 L of water through a pre-weighted and pre-dried (110 $^{o}$C for 24 h) Whatman GF/F glass fiber filter. The filter was then oven dried at 120$^{o}$C for 2 hours, and the initial and final weights recorded. Chlorophyll-a concentration was measured by filtering 2 L of surface seawater through a 1.2 μm Whatman GF/F filter, and the filters were immediately frozen at 4°C and stored in the dark. The samples were macerated with acetone 90 %, centrifuged, and the extracts were read in a spectrophotometer as described by tri chromatic method (Eaton *et al.,* 1995).

**Statistical analyses**

Temporal and spatial similarity of sampling points was calculated applying the Euclidian distance for Cluster analysis and non-metric multi-dimensional scaling ordination analysis (MDS). Statistical analyses were performed using Primer 5 (PML- Plymouth Routines in Multivariate Ecological Research, Ivybridge, United Kingdom) and Statgraphics Plus for Windows (Statistical Graphics Corp, Princeton NJ, U.S.A.). Variations in nutrient concentrations as a function of the distance between sample stations and the control station, as well as variations in nutrient concentrations between surface samples and bottom, were calculated using two-way ANOVA.

**Simulations of farm operations and impact to ambient water quality**

The AquaModel software is a simulation program used to describe and analyze both farm operations and their environmental impact on coastal or offshore waters (Figure 2). The model comprises five sub-models 1) circulation, 2) farm operations, 3) fish metabolism, 4) plankton and 5) benthic.

Each one of the sub-models required specific inputs like field data, stored ocean data and satellite imagery, to calculate and generate a variety of outputs like 4D-modeling, graphs and tables of key parameters including oxygen, particulate organic waste, dissolved nutrient wastes, fish growth rate, biomass, etc. Table 1 summarizes the inputs and outputs for each one of the sub-models. The field measurements of current velocity, temperature, oxygen, nitrogenous nutrients, phosphate, and chlorophyll were tabulated and introduced into the AquaModel software to produce a simulation model of the operations and impact by the cobia farm. Our model of the cobia farm provided a time series of maps of the calculated distribution of water quality variables that were perturbed by the cobia farm. Additionally, parameters such as stocking density, pellet size, feeding rate, and survival rate for each cage were also introduced into this simulation model.

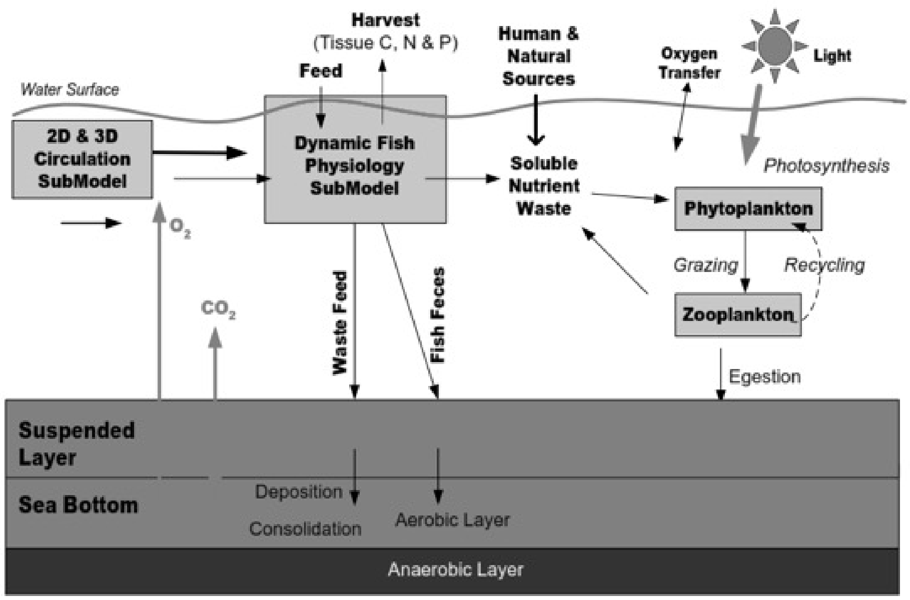



**Figure 2**. The processes simulated using the AquaModel software of the Tierrabomba Island cobia farm. Details are found in text.

Information on *R. canadum* metabolism that was used to calculate or estimate the values for coefficients found in the equations of the subroutine, came from two sources. Specifically, growth information was acquired from wild fish from *Fishbase* http://www.fishbase.org/search.php. The results of tuning our metabolic model to the Von Bertanlanffy growth equation showed that by simply tuning 3 coefficients in our equations we could obtain excellent fits. For example, Figure 3 shows the maximum specific growth rates of cobia (fractional increase in weight per day) as a function of size predicted from the Von Bertanlanffy equation presented in *Fishbase*, which is predicted also from Aquamodel's metabolic subroutine.

To increase prediction accuracy, adjustments were made to the submodel of cobia growth and metabolic activity. It was possible to adjust the equations with the data obtained in the culture. The modified functions included specific growth rate/day, environmental specific growth and weight limit specific growth. The maximum weight of the cobia was set at 6 kg. The specific daily growth rate was expressed in terms of weight of the fish, ranging from over 7 % per day in the first months of life to only 0.5 % per day at the end of the first year. The specific growth rate of the cobia also varied with temperature, ranging from a minimum threshold of growth of 16 ºC and a maximum threshold of growth of 33 ºC. Maximum growth was set at a temperature of 27 ºC.

**Table 1.** Summarize of inputs and outputs for each one of the sub models for the AquaModel.

| | Sub Models | | | | |
|---|---|---|---|---|---|
| | **Circulation** | **Farm operations** | **Fish metabolism** | **Plankton** | **Benthic** |
| Inputs | Current velocity<br>Bathymetry<br>Boundary conditions | **Farm setup**<br>Specie<br>Cage location (latitude, longitude)<br>Cage size (m$^3$)<br>Stocking density (number of fish/cage)<br>Average weight of stocked fish (kg/fish)<br>**Farm operations**<br>Feed rate (kg/day/wet weight)<br>Harvest schedule (date of harvest)<br>Harvest biomass<br>Estimate percentile of uneaten feed loss from the cages | Water temperature<br>Ambient oxygen concentration<br>Ambient current velocity | Concentration of oxygen, inorganic nitrogen, chlorophyll-a | Current velocity |
| Outputs | Time series of 3D distribution of current velocity<br>Superficial and bottom flow velocity | Time series of weight, growth, rate and number of fish within each cage | Specific growth rate<br>Specific daily growth<br>Egestion rate | Time series of the concentrations of dissolved inorganic nitrogen and oxygen, phytoplankton and zooplankton | Particulate & Dissolved Waste Tracking |

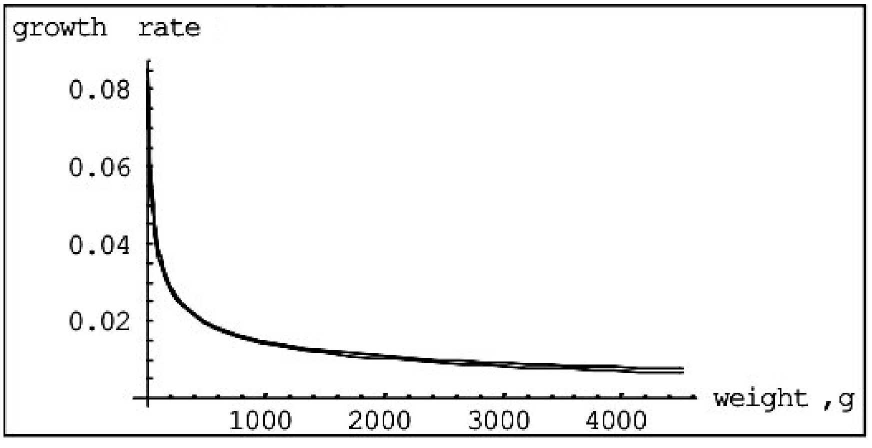



**Figure 3**. Specific rates of growth for cobia as a function of individual size as calculated from the Von Bertalanffy growth equation and our metabolic subroutine.

Previous lab trials with cobia are incorporated like assumptions in this sub routine, including equations for oxygen-limited metabolism, a key feature by its importance in farms where fish are cultured at relatively high densities and in waters of moderate or lower dissolved oxygen concentration. Dissolved oxygen is a primary limiting factor to net pen carrying capacity and is therefore of considerable modeling interest. Data on respiration rate at different swimming speeds came from laboratory measurements by O'Brien, Kiefer & Rensel (2011). This report provides a detailed description of not only the fish metabolic subroutine but also all other *AquaModel* subroutines.

## RESULTS

### Culture parameters

During the course of the study there were 162 353 fish introduced into the cages, and consuming 314 metric tons of feed. Initial biomass was 3 metric tons, reaching a total biomass during the study period of 307 metric tons. There were five commercial production groups with different sizes (Table 2). The survival rate ranged from 88-90 %. At harvest the average weight was 4.4 ± 0.3 kg and the total length was 758 ± 26 mm.

**Table 2.** Commercial production and food intake from May to December in 2011.

| Commercial group | Stocking date | Total stocking fingerlings | Total feed intake (fg) | Culture stages |
|---|---|---|---|---|
| (Kg) | July 2010 | 32600 | 101 006 | Grow-out 2 and harvest |
| B | December 2010 | 22275 | 124 250 | Grow-out 2 |
| C | April 2011 | 17793 | 49 326 | Grow-out 1 and 2 |
| D | June 2011 | 33014 | 27 011 | Nursery and grow-out 1 |
| E | August 2011 | 56671 | 12 612 | Nursery and grow-out 1 |

### Oceanic currents at the cage site

A total of 12247 data points were recorded with the current meter. In general, average current speed was higher at the bottom (11.4 ± 7.2 cm/s) than at the water surface (7.9 ± 4.8 cm/s) ($p < 0.05$). The highest values of 82 cm/s at surface and 59 cm/s at bottom were recorded in May. Fifty-six percent on the readings corresponded to values from 0 – 10 cm/s, 42 % from 10 – 30 cm/s and only 1.6 % of the values were higher than 30 cm/s. From May to November a bidirectional trend was observed at surface, whereas at the bottom it was mainly unidirectional. From May to August the trends were NE in both, surface and bottom, and from September to November the surface trends were SW and S, while at the bottom were E and SE. In December an abrupt change on direction was observed in the surface S, NNW, SW, and for the bottom S, WNW, NW (Table 3). Tide did not have influence in the currents for this region and average variation in sea level was only 0.5 m according to forecast high and low tide (CIOH, 2011).

### Physical-chemical variables

Surface temperature ranged from 27.4ºC to 32.4ºC, with higher values from June to November. Bottom temperature recorded with the current meter increased from May to November, 27.6 ± 0.4 ºC to 29 ± 0.2 ºC and then decreasing again (Table 4).

**Table 3.** Bottom and surface current velocities average and direction at the cobia culture farm from May to December in 2011.

| | | Surface | | Bottom | |
|---|---|---|---|---|---|
| | | **Velocity (cm/s)** | **Main direction** | **Velocity (cm/s)** | **Main direction** |
| **MAY** | Average | 8.6±5.9 | NW | 9.8±7.2 | NE |
| | Min | 0.0 | | 0.0 | |
| | Max | 82.0 | | 59.0 | |
| **JUN** | Average | 7.1±4.8 | N | 9.0±6.1 | NE |
| | Min | 1.0 | | 1.0 | |
| | Max | 21.0 | | 33.0 | |
| **JUL** | Average | 6.9±4.6 | N | 11.8±8.2 | NE |
| | Min | 0.0 | | 0.0 | |
| | Max | 37.0 | | 59.0 | |
| **AUG** | Average | 7.9±4.2 | E | 10.9±5.6 | E |
| | Min | 1.6 | | 1.2 | |
| | Max | 23.8 | | 33.8 | |
| **SEP** | Average | 8.7±4.9 | S | 11.7±7.2 | E – SE |
| | Min | 1.7 | | 1.7 | |
| | Max | 29.2 | | 49.5 | |
| **OCT** | Average | 7.6±4.6 | S -SW | 12.1±7.9 | E – NE |
| | Min | 0.0 | | 0.0 | |
| | Max | 29.0 | | 43.0 | |
| **NOV** | Average | 8.6±4.9 | S | 14.3±9.0 | E – SE |
| | Min | 2.0 | | 0.0 | |
| | Max | 33.0 | | 51.0 | |
| **DEC** | Average | 8.3±4.9 | SW | 11.9±6.6 | NW |
| | Min | 1.7 | | 2.3 | |
| | Max | 36.7 | | 37.8 | |

Salinity range was 23 to 37 PSU, with an average of 31.4 ± 3.2 PSU. The lowest average value in surface, 28.3 ± 4.6 PSU occurred in October and November, corresponding to the peak of the rainy season.

For the vertical sampling points, the average value in surface was 30.0 ± 1.84, 31.9 ± 3.3 at the middle and at bottom 32.8 ±1.8 PSU at the bottom. pH values varied from 7.8 – 8.5 and were not affected by the seasons, without variability during the sampling period, The lowest average value 7.99 ± 0.11 was registered at the deeper sampling points (p-value <0.05), while in middle was 8.20 ± 0.12 and in surface was 8.23 ± 0.11.

Dissolved oxygen values ranged from 4.32 to 6.79 mg/L, the lowest average 5.2 ± 0.4 was found during the rainy season, mainly on October and November. DO values also varied according to the vertical distribution with the lowest values at the bottom, 5.0 ± 0.52 mg/L, and the highest at the surface, 5.8 ± 0.4 mg/L. DO levels inside the cages averaged 5.6 ± 0.3 mg/L at morning (08:00) and 5.7 ± 0.2 at evening (17:00).

**Table 4.** Physicochemical variables (temperature, salinity, nutrients and suspended solids) reported in the study area.

| Variable | Vertical variation (p-value <0.05) | Horizontal variation (p-value <0.05) | Season and month variation (p-value <0.05) | Max | Min | Season | Range |
|---|---|---|---|---|---|---|---|
| Transparency (m) | | z | ** Rainy Oct - Nov | 15.0 | 3.0 | Transition | 10.42 ± 1.52 |
| | | | | | | Rainy | 5.63 ± 2.51 |
| | | | | | | Dry | 14.88 ± 0.25 |
| pH | ** Bottom | ** EP1-B EP2-B EP3-B EP4-B | ** Dry December | 8.46 | 7.81 | Transition | 8.06 ± 0.1 |
| | | | | | | Rainy | 8.16 ± 0.17 |
| | | | | | | Dry | 8.30 ± 0.04 |
| Salinity (UPS) | ** Surface | ** EP1-S EP2-S EP3-S EP4-S | ** Rainy Oct - Nov | 37 | 23 | Transition | 32.29 ± 1.54 |
| | | | | | | Rainy | 30.46 ± 4.08 |
| | | | | | | Dry | 32.09 ±1.16 |
| Temperature (°C) | ** Bottom | ** EP1-B EP2-B EP3-B EP4-B | ** Transition May | 32.4 | 26.4 | Transition | 29.35 ± 1.38 |
| | | | | | | Rainy | 29.49 ± 0.72 |
| | | | | | | Dry | 28.58 ± 0.20 |
| D.O. (mg/L) | ** Bottom | | ** Rainy Oct - Nov | 6.79 | 4.32 | Transition | 5.70 ± 0.53 |
| | | | | | | Rainy | 5.31 ± 0.58 |
| | | | | | | Dry | 5.57 ± 0.64 |
| TSS (mg/L) | | | ** Rainy Oct - Nov | 33.0 | 7.5 | Transition | 17.0 ± 4.8 |
| | | | | | | Rainy | 21.7 ± 6.4 |
| | | | | | | Dry | 9.7 ± 1.5 |
| Nitrate (µg at N /L) | ** Bottom | | ** Rainy Sep - Nov | 5.09 | 0.25 | Transition | 0.91 ± 0.47 |
| | | | | | | Rainy | 2.24 ± 0.99 |
| | | | | | | Dry | 0.78 ± 0.48 |
| Nitrite (µg at N/L) | | | ** Transition August | 0.19 | 0.04 | Transition | 0.09 ± 0.02 |
| | | | | | | Rainy | 0.11 ± 0.04 |
| | | | | | | Dry | 0.11 ± 0.01 |
| Ammonium (µg at N/L) | | | ** Rainy Oct - Nov | 33.21 | 5.81 | Transition | 8.91 ± 1.40 |
| | | | | | | Rainy | 18.62 ± 9.85 |
| | | | | | | Dry | 11.82 ± 0.91 |
| DIN (µg at N /L) | | **EP1 EP2 EP3 EP4 | ** Rainy Oct - Nov | 37.16 | 6.22 | Transition | 9.91 ± 1.62 |
| | | | | | | Rainy | 20.97 ± 10.61 |
| | | | | | | Dry | 12.71 ± 1.01 |
| Reactive Phosphorus (µg at P/L) | ** Surface | ** EP1-S EP2-S EP3-S EP4-S | ** Rainy Sep - Nov | 1.55 | 0.04 | Transition | 0.62 ± 0.24 |
| | | | | | | Rainy | 0.79 ± 0.44 |
| | | | | | | Dry | 0.43 ± 0.23 |
| Chlorophy-ll-a(mg/m$^3$) | | | ** Dry December | 1.3 | 0.2 | Transition | 0.58 ± 0.12 |
| | | | | | | Rainy | 0.34 ± 0.09 |
| | | | | | | Dry | 0.94 ± 0.24 |

**Suspended solids**

No significance differences were found in vertical and horizontal distribution of total solid suspended TSS, but there are temporal changes. The values were strongly affected by discharges of El Dique channel in October and November at the four stations. During the rainy season TSS averaged 21.7 ± 6.4 mg/L, while in transition and dry season TSS average values were 17.0 ± 4.8 and 9.7 ± 1.5 mg/L, respectively (Table 4).

**Nutrients and primary productivity**

Ammonium levels varied from 5.8 - 33.2 µg-at N/L, nitrate levels from 0.2 - 5.1 µg-at N/L and nitrite from 0.04 _ 0.19 µg-at N/L. These ranges are particularly high and reflect the influence of sewage and drainage from diverse industrial activities in Cartagena city. For the three compounds, the concentrations varied significantly with seasons and sampling stations. In terms of the horizontal distribution of sampling points, nitrogen compounds were significantly higher in the points closer to the cages (p-value <0.05) particularly at depth of 5 and 30 m. The nitrate fraction varied significantly with depth with a lower average at bottom. Dissolved inorganic nitrogen (DIN) was largely ammonium fraction, generally 70 %, and was higher during rainy season with an average value of 21 ± 11 µg-at N /L. A horizontal trend was found for ammonium, with lower values at the stations EP3 and control point EP4 (p-value <0.05) (Figure 4).

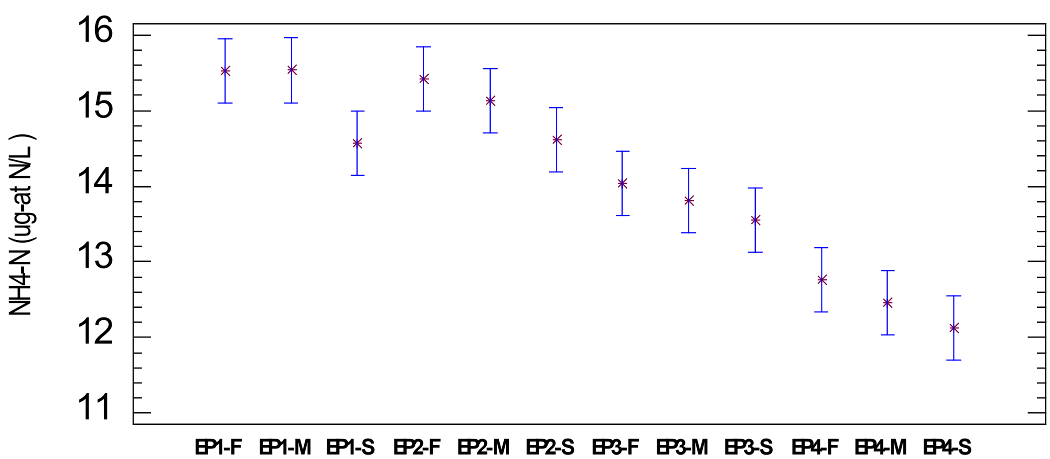



**Figure 4**. Ammonium variation with higher values in EP1 and EP2 closest to the crop. B= Bottom, M= Middle, S= Surface.

Phosphorus ranged from 0.04 – 1.55 µg-at P/L with an average 0.68 ± 0.37 µg-at P/L. Higher values occurred during the transition 0.6 ± 0.2 and rainy season 0.8 ± 0.4, and lower values occurred during the dry season 0.4 ± 0.2 µg-at P/L. In terms of vertical distribution, the lowest average was in surface waters 0.44 ± 0.24 while higher values were found at intermediate depths, 0.69 ± 0.30 and at the bottom 0.92 ± 0.40 µg-at P/L.

The concentration of chlorophyll-a values ranged from 0.2 – 1.3 mg/m$^3$. During October and November, chlorophyll-a concentration was lower 0.3 ± 0.1 mg/m$^3$, coinciding with the high TSS values and increased discharges from El Dique channel. Temporal classification of these parameters showed three groups (Figure 5).

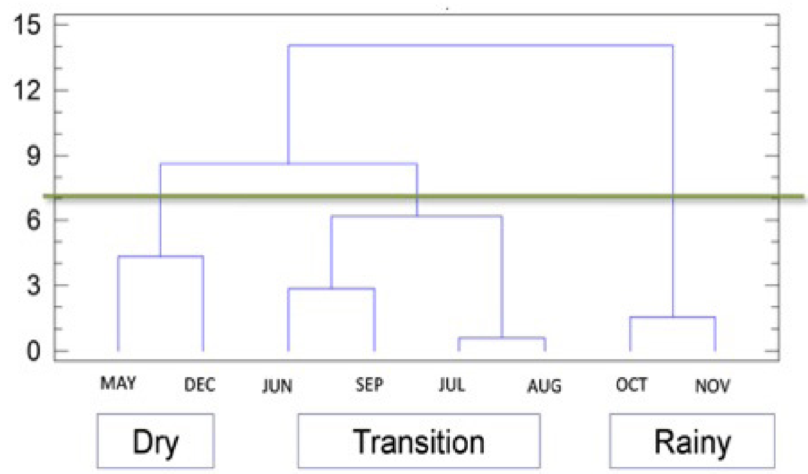



**Figure 5**. Temporal analysis dendrogram for dissolved inorganic nitrogen (DIN) and phosphorus applying Euclidian distance.

1. In October and November, the values of DIN, 30.8 ± 4.3 µg-at N/L, were the highest and caused by the higher discharge from El Dique channel that was driven by due to very heavy rainfall.

2. May, which is considered the transition period, exhibited lowest phosphorus values 0.56 ± 0.2 µg-at P/L. On the other hand, similar low values also occurred in December.

3. From June to September DIN and phosphorus concentrations increased moderately. Again, this increase was expected because of the flow dynamics of the El Dique channel and Cartagena Bay. Spatial variation also showed significant differences (p-value <0.05) between sampling stations, with higher values in EP1 and EP2 which were closest to the cages and a progressive decrease at stations more distant from the cages (Figure 4).

**Modeling**

Our cobia simulation model required 3 hours to complete its computations, but the results of these computations were stored in a binary file that was then run to completion in less than 10 minutes.

Here in Figure 6 we display three snapshots from our simulations- one for each of the 3 climatic seasons. In these figures one sees a base map, 2 legends, 4 plots and a status window of the time, date, and the co-ordinates of the center of the map. The base map contains a rectangle which marks the boundary of the computational array of the simulation. Within this rectangle, red dots might be seen, which the sampling stations are. An additional red dot is outside the rectangle which is the control station. The false color raster image shows the distribution of dissolved inorganic nitrogen at a depth of 5 meters that is produced by the excretion of ammonia and urea of the cultured fish in the 3 sampling points. The color code of DIN is in the upper right hand corner of the image. The red line transects the plume of DIN, and the distribution of DIN along this line is shown in the left hand plot that is second from the top plot.

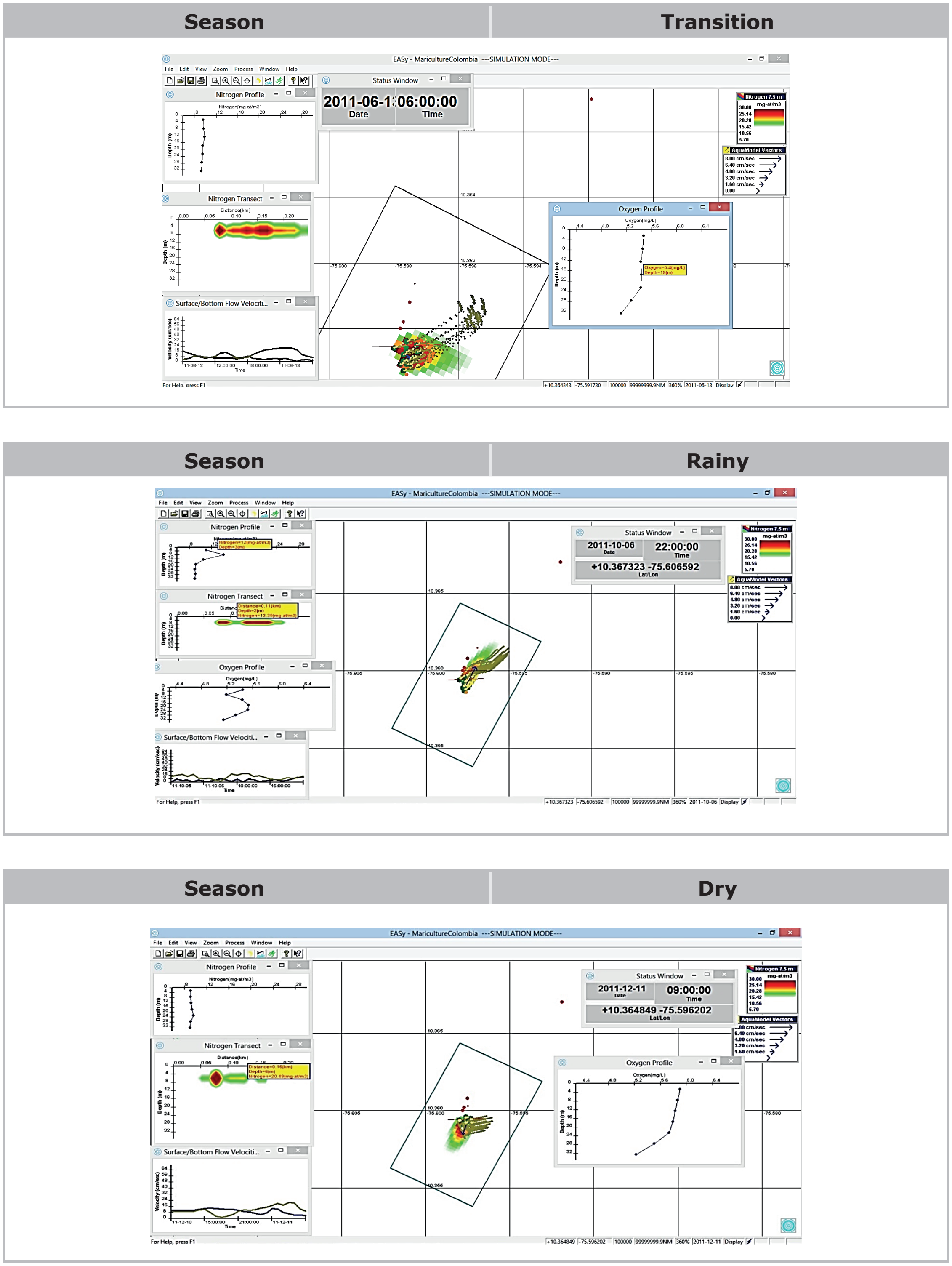



**Figure 6.** Snapshots of selected time steps in the AquaModel simulation of the Tierrabomba farm. The dates and time of these time steps are shown in the status window in the upper right hand corner. The 3 times steps occur within the transition, rainy, and dry seasons. See text for a description of the base map, plots, and legend.

The line of green dots shows the trajectory of the feces produced by the caged fish as they are transported to the sediments; the line of yellow dots shows the trajectory of the uneaten food from the cages to the sediments. The uneaten food has a much higher sinking rate than the feces and thus is deposited closer to the cages. Both the uneaten food and the feces provide food for the benthic community in the vicinity of the farm. These waste materials can also be transported further from the farm if bottom currents exceed a threshold value.

The blue error in the center of the base map is a vector whose length and direction is determined by the velocity of the surface currents as measured by the Doppler Current Profiler deployed during the sampling period. The plot in the lower left hand corner of the figure shows the recent time series of current speed at the surface and near the bottom. Finally, the plot in the upper left corner of the figure is a profile of the vertical distribution of DIN at the location indicated by the orange dot, and the plot on the left of the figure is a profile of the vertical distribution of oxygen at the location indicated by the orange dot.

As the dissolved wastes produced by the fish are transported away from the farm, they are assimilated by plankton, and the particulate wastes consisting of feces and uneaten food sink as they are carried by currents away from the farm. These wastes will be deposited in the sediment, resuspended and transferred further from the farm (at better sites), and eventually assimilated and remineralized by benthic and other organisms.

The model describes these processes for three tracer elements, oxygen, nitrogen, and carbon. Oxygen is the most important since the high density of fish within the farm can significantly reduce its concentration both within the farm and within the plume of dissolved waste that is formed downstream of the farm. The concentration of oxygen within the farm can affect the growth and metabolic activity of the fish and will vary with ambient concentrations, the size and stocking density of the farm, the metabolic activity of the fish, and the rate of water flow through the farm. The concentration of oxygen within the plume of dissolved waste will be restored to ambient concentration at a rate that will be determined by turbulent mixing, the rate of photosynthesis by phytoplankton, and if the plume is at the surface, the rate gas exchange at the water's surface. As discussed below, oxygen is also most important to the health of the benthic community beneath the farm.

Nitrogen is also important since in many tropical or semitropical environments, and in some seasons in temperate seas, it may limit the growth of phytoplankton in coastal waters. Nutrient loading of the water column can cause algal blooms and possibly harmful algal blooms. The concentration of nitrogen within the farm will vary with ambient concentrations, the size and stocking density of the farm, the metabolic activity of the fish, and the rate of water flow through the farm. The concentration of nitrogen within the plume of dissolved waste will be restored to ambient concentration at a rate that will be determined by turbulent mixing, and the nitrogen uptake rate of photosynthesis by phytoplankton.

Carbon is the third important component because the supply of particulate carbon from feces and uneaten food to the sediments is respired by benthic organisms and may result in a depletion of interstitial sediment oxygen. If the carbon loading of the sediments creates a demand for oxygen that exceeds its supply from the overlying waters, the sediments may become anaerobic, causing dramatic changes in the benthic community as well as the production of hydrogen sulfide and other reduced compounds that will mix with the overlying waters.

## Discussion

Intensive fish aquaculture has been associated with the production of high loads of dissolved nutrients and particulate organic matter, affecting the surrounding environment, by causing blooms of harmful algae and sediment deposition on seabed beneath the cages. If severe such wastes cause biodiversity loss in benthic communities, like in Tolo Harbour or Bolinao in Asia, (San Diego *et al.,* 2008)

(Lee & Wong, 1997). From the perspective of the farmer, waste production is also important since the profitability of the farm depends in part on whether fish are properly fed without wasting expensive and nutrient-rich food. Both in situ sampling like simulation models, have identified that the main negative effects are sediment deposition on the seabed, and the increase in ammonium and phosphorus by the release of wastes through the year in concentrated production areas with thousands metric tons per year (Naylor & Burke, 2005; Seymour & Bergheim, 1991).

Before establishing the cobia farm in Colombia, we conducted review of environmental conditions at the farm. The review included the historical data (Table 5) reported by Lonin, Parra, Andrade, and Thomas, 2004 and Tuchkovenko and Lonin, 2003. From those studies, it was evident, that the site receives both, the influence of water from Cartagena Bay as well as discharge from El Dique channel particularly during the rainy season. Available historical information showed an average total nitrate discharge from El Dique channel of 12.0 x $10^3$ ton/year and total phosphate 3.0 x $10^3$ ton/year. Such eutrophication in coastal areas by increased human activities is indeed a situation that has been recorded worldwide. Such processes also lead to unbalanced flows of nitrogen and phosphorus (Islam & Tamaka, 2004). This phenomenon along the Cartagena coast shows a sustained increase in recent decades, reaching values of nitrate at ~8 mg/L and total nitrogen of 20 to 30 mg –at/L (Cloern, 2001).

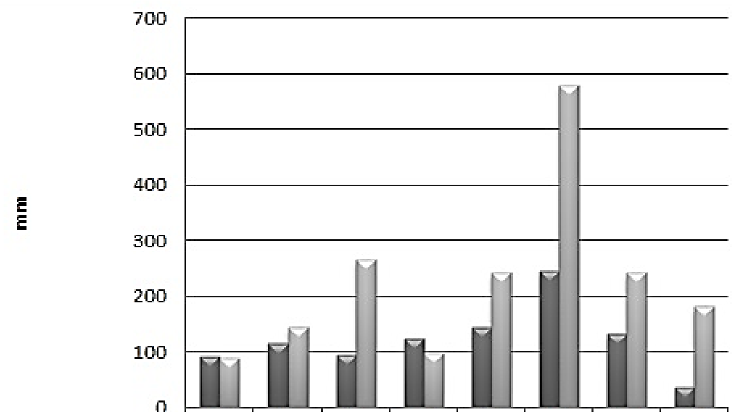
Variations in nutrient levels at the cobia farm and at the control station were mainly explained by seasonal changes in the environment rather than by the fish-farming activities. Concentrations of nitrate, ammonium, and phosphorus were significantly higher during the rainy season. An atmospheric cold phase during 2011 caused a significant increase in rainfall both inland and on the coast (Figure 7), and therefore discharges from El Dique channel increased significantly. In contrast, chlorophyll-a values increased during the dry-season 0.94 ± 0.24 mg/m$^3$. The relevance of the seasons on the nutrient load for fish farms has also reported by Ruiz *et al.,* (2001) and Maldonado *et al.,* (2005).

In terms of the net effect of the culture site, nutrient analysis from the different sampling stations, showed increased loads of nitrogen and phosphorus up to 100 meters from the cage, and no influence beyond that point. The profile of nitrogen for a point 300 m away from the farm showed values ranging from 8 to 14 µg –at N/L. There are several reasons why the production of DIN by the farm will not cause phytoplankton blooms. First, the plume is too small and too transient to lead to blooms. Second, the concentration of DIN in ambient waters already exceeds the threshold for saturated growth rates of phytoplankton. Third, phosphate rather than DIN appears to be the limiting nutrient for phytoplankton growth not nitrogen. Most of the phosphate produced by the cobia farm is lost as uneaten feed and feces and thus will be transported to the sediments or deep waters where phytoplankton growth is limited by light. The high load of sediments by El Dique channel during rainy season interferes the sunlight into the column water.

According to the simulations, that despite seasonal variability the plume of DIN enriched water down stream of the farm never reached more than 300 meters downstream of the farm for an extended period of time. Also, this plume never reached deeper than 12 meters. Although the model predicted significant increases in DIN within the farm, the concentration of DIN quickly decreased and the dissolved wastes were transported from the farm. The simulation also indicates that under the stocking density of the fish and the ambient conditions of current velocity and oxygen concentrations, the growth rates of the cobia were never limited by the concentration of oxygen within the cages.

**Table 5.** Prior information for nutrients and other variables in column water and physical conditions near to culture site (Sampling Station INVEMAR 10.3623505 / -75.599906).

| | Variable | Values |
|---|---|---|
| **Water Quality** | Nitrates (NO3) | Dry 1.19 µg-at/L<br>Rainy 0.78 µg-at/L |
| | Ammonium (NH4) | Dry 4.18 µg-at N/L<br>Rainy 17.34 µg-atN/L |
| | DIN | Dry 5.88 µg-at/L<br>Rainy 27.41 µg-at/L |
| | Reactive phosphorus | Dry 0.66 µg-at/L<br>Rainy 1.07 µg-at/L 1 |
| | TSS | Dry 30.1 mg/L<br>Rainy 40.7 mg/L |
| | Dissolved Oxygen (OD) | Dry 7.2 mg/L<br>Rainy 6.8 mg/L |
| | Transparency | Dry 20-25 m<br>Rainy 15 – 18 m |
| | Salinity | Dry 35 °/oo<br>Rainy 32 °/oo<br>22-33 °/oo Surface<br>35 °/oo Bottom |
| **Seabed** | Composition | Arcilla 86 % |
| **Physical and meteorological conditions** | Current Direction | Dry N - NE<br>Rainy E-SE |
| | Current speed average (6m depth) | 11.5 cm/s |
| | Depth | 30-45 m |
| | Wind speed average | 8 knots |




| | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|
| Media plurianual (1941-2010) | 92 | 115 | 94 | 124 | 144 | 244 | 132 | 37 |
| 2011 | 87,5 | 143,2 | 264,9 | 97,7 | 242 | 579,9 | 241,3 | 180,1 |

**Figure 7.** Comparative graphic for rainfall during 2011 vs. multi annual average at the region (CIOH, 2011).

Based on experiences in offshore aquaculture in other countries, the presence of permanent currents with average speeds of one knot (~50 cm/s) has been a key parameter for site selection; such flow rates provide adequate oxygen supply and ensure the dilution of nutrients produced by the farm. We note that under extreme conditions when current speed exceeded 30 cm/s toward the northeast, that the track of feces reached the control station 1 km far away from the culture site. Under extreme conditions when the current speed was low and the final cage near peak biomass, the concentration of oxygen within the cage was 4.4 mg/L. This value is above the threshold that begins to limit the growth rate of the cobia.

The cobia simulation model yielded calculations that had a high degree of concordance with the sampling data. Cages generated particulate organic material composed mainly of feces and unconsumed food. From the model we calculated a 5 % loss of daily supplied food. In the simulation it was possible to trace the path of the food waste and feces in the direction of the prevailing current. A study in fish farms in the Mediterranean showed that up to 80 % of the particulate material that escaped from the cages was consumed by wild fish before it reached the bottom (Vita *et al.,* 2004). In our study, we also found an increase in fish communities around the cages, since the culture was established. It could be due to the attraction by anchoring structures and/or the utilization of the generated waste. However, understanding the dynamics of the interaction between wildlife and culture is a subject of another study and such processes were not included in the simulation.

The cobia model also predicted that oxygen concentrations would be kept above 5.2 mg/L throughout the sampling period. Records taken by the farmer inside the cage were in agreement with the model. We note however that during the period of high influence from the El Dique channel, a slight decrease in the oxygen was detected due to a decrease in phytoplankton production (Cañón, Tous, López & Orozco, 2007). Such process was not simulated in our runs.

While the model calculated a maximum weight of 6 kg growth after 1 year, field measurements indicated that the general population had an average weight of 4.4 kg after 1 year. However, this difference could be explained by the sexual dimorphism found in the population, with females being significantly larger than males. In this sense, the model would be ideal for explaining the growing in a female monosex population, which will reach their potential target weight equation in its first year.

In this study we found that 60 to 70 % of this fraction corresponded to ammonium, which is consistent with the biological information of cobia. This species grows very fast and thus excretes urea at a high rate. Studies indicate that urea is rapidly degraded to ammonium (Sun & Chen, 2009). Despite the high rate of DIN production in the cages the current velocities at the farm ranged from 7 to 50 cm/s. Our calculations indicated that such flow continuously replaced the total volume of the cage at a rate of 13-327 times per minute respectively.

We have compared the results found during our research with farms with similar levels of production- such as those reported for Greece and Spanish farms (Table 6). According to the reports from the Western Mediterranean, phytoplankton in the ambient waters of fish farms is limited by phosphorus rather than nitrogen, and algae and bacteria quickly assimilate the dissolved nutrients from the cages. It should be noted that these farms grow mainly bass and sea bream, species which grow to a weight of 0.5 to 1.5 kg in a year, significantly less than cobia.

**Table 6.** Comparative results for nutrients in different offshore marine fish aquaculture experiences.

| Author | Specie | Common name | Site | Trophic characteristic | Oceanographic conditions | Number of cages and annual production | Nutrients in column water |
|---|---|---|---|---|---|---|---|
| Present study | *Rachycentron canadum* | Cobia | Tierrabomba island Colombia Caribcean Sea | Eutrophic | 500 m from coast<br>Depth 35m<br>Average surface current speed 7,9 ± 4,8 and bottom speed 11,4 ± 7,2 cm/s | 8 cages<br>~ 400 ton/yr | Nitrate 0,25-5,09 µg-atN/L<br>Ammonium 5,81-33,21 µg-atN/L<br>Reactive phosphorus 0,04 – 1,55 µg-atP/L |
| Mantzavrakos *et al.*, 2007 | *Sparus aurata*<br>*Dicentrarchus labrax* | Besugo<br>Lubina | Plateia Island<br>Greece<br>Mediterranean Sea | South to north chlorophyll gradient<br>Upwelling in summer | 150 m from coast<br>Depth 40 m<br>Not references current speed | 350-400 ton/year | Ammonium 0,4-2,2 µg-atN/L<br>Reactive phosphorus 0,04-1,55 µg-atP/L |
| Mejía, 2005 | *Rachycentron canadum*<br>*Lutjanus analis* | Cobia<br>Huachinango | Culebra Island<br>Puerto Rico<br>Caribbean Sea | Oligotrophic | 3 km from coast<br>Depth 28 m<br>Average surface current speed 20-30 cm/s | 2 cages<br>40 ton/year | Ammonium 0,21-2,29 µg-atN/L<br>Total phosphate 0,06-0,45 µg-atP/L |
| Maldonado *et al.*, 2005 | *Sparus aurata*<br>*Dicentrarchus labrax* | Besugo<br>Lubina | Eastern coast<br>Spain<br>Mediterranean Sea | P-limited | Depth 21-37 m | 8-18 cages<br>40-549 tons/yea | Nitrate 0,5-4 µg-atN/L<br>Total phosphate 0,1-0,5 µg-atP/L |

In reference to cobia culture, there is one report of cobia growth in 2 submerged cages in open waters off Culebra Island, Puerto Rico. During the period 2002–2003, Mejía (2005) recorded surface currents at this farm from 20 to 30 cm/s. He also found values for the concentration of ammonia varied from 0.21 - 2.29 µg –at N/L, and values for phosphorus varied 0.06 to 0.45 µg –at P/L. These values are significantly lower than those that we measured. This difference may be explained by the fact that the Puerto Rico cobia farm was located in oligotrophic waters, near coral reefs, and without significant contributions of inland water for most of the year. On the contrary, as previously described, the cobia culture studied in the present research is strongly influenced of El Dique channel and Cartagena Bay, so it can be considered eutrophic system.

## Conclusions

During the eight-month period of this study, 307 metric tons of cobia were grown. This production is impressive, and is best explained by a proper feeding schedule for the fish and the continuous supply of oxygen to the cage by the continuous yet moderate currents that are found in the coastal water off Tierrabomba. Growth rates were high even though average monthly current velocities were never higher than 8 cm/s.

The information collected in the field and the three dimensional maps of water quality variables calculated with our cobia simulation model helped us to visualize in spatial and temporal detail the dynamics of fish metabolism and waste production by the farm. Both the field measurements and model simulation revealed rapid dilution of nutrients in the downstream of the cages, and no hypoxia occurred within the cages.

Strong precipitation due atmospheric cold phase during 2011 caused large increases in discharges by El Dique channel. This increase in discharge led to increases in both turbidity and nutrient concentrations in receiving waters; however, such increases had no impact on the farm.

Calculations with our cobia farm simulation of oxygen, nutrient and chlorophyll-a concentrations were consistent with those found during the field study. This agreement indicates that despite the dynamic nature of the farm and coastal water conditions, the simulation model provides a good description of the growth and metabolism of the fish culture as well as the concentration of nutrients and oxygen as it is transported from the farm. The AquaModel software, which provides a comprehensive and detailed spatial and temporal description, appears to be significant advanced over earlier simulation models of waste production by fish farms. It appears to be an attractive tool for managing the licensing and monitoring of fish farms.

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