Aquaculture Monitoring, modeling and performance standards for net pens

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Seriola and Cobia Aquaculture Dialogue (SCAD)
19-20 February 2009  Seattle, Washington
Overview

- Water quality and benthic effects
- Measurement methods for monitoring: temperate oriented, what about tropics?
- Suggested overarching goals for siting
- Brief overview of simulation modeling (cobia)
Benthic Performance Measures and Standards

Benthic infauna community analysis is the best measure if baseline is available. The ultimate test and used still...

Pros: Direct measurement of biological effect
Cons: Sometimes relatively expensive
Reference (control) area selection is serious problem

Surrogate Measures of infauna effect:
1) Organic carbon from cores or grabs
2) Free sulfide probe
3) Redox (oxidation-reduction potential) probe
4) Video-drop camera (gross bottom impact and feed loss)

1-3 for soft bottoms, 2 cm standard, 4 for all bottoms
Total Organic Carbon (TOC)

Pros:
1) direct measure of the cause of the effect (oxygen demand during assimilation and microbial or macrofauna respiration)
2) Easy to sample, process and ship to laboratory
3) High accuracy in normal commercial or university labs
4) Widely used in characterizing the sea bottom

Cons:
1) Third world countries, lack of sufficient laboratory support
2) Cost is possibly higher than in field assays, but not compared to capital and maintenance costs of field assay methods
3) TOC varies naturally with the amount of silt and clay, so some samples are often taken to classify or stratify results

Where used: Washington State since <1986, Norway, Some Canadian areas, applicable to Caribbean, Hawaii
Total Organic Carbon “Triggers”
Not to exceed levels

<table>
<thead>
<tr>
<th>Category Number</th>
<th>Mean Percent Silt and Clay in Sample</th>
<th>Total Organic Carbon, Trigger Value</th>
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<tr>
<td>2</td>
<td>20-50%</td>
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<td>4</td>
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Sulfides (electrode)

**Pros:**
1) Measurement in field after some processing
2) Easy to relate to degree of eutrophication for some ecoregions and cultured fish species, principally salmon in higher latitudes.
3) Methodology is published

**Cons:**
1) Useful only in relatively soft sediments (silt/clay) Sands?
2) Precision and accuracy variable.
3) Some controversy about what is actually measured
4) Equipment is expensive
5) Required extensive and frequent calibration
6) Varies significantly by depth of a few millimeters

Where used: Canada* and Maine in combination with other measures
Chamberlain and Stucchi 2007
British Columbia
(Sulfides probe monitoring, proposed for 2009)

700 uM at 30 m at “Peak production” to Maintain background

4,500 uM at 30 m at “Peak production” to Maintain polychaetes
Redox (electrode)

Pros: (same as sulfides)
1) Measurement in field relatively easy
2) Results are easy to relate to degree of eutrophication for some ecoregions and cultured fish species, principally salmon in higher latitudes.
3) Methodology is published

Cons: (Same as Sulfides plus more)
1) Useful only in relatively soft sediments
2) Precision and accuracy variable.
3) Some controversy about what is actually measured
4) Equipment is expensive
5) Required extensive and frequent calibration
6) Varies significantly by depth
7) Probe poisoning

Where used: widely discredited now, no longer used in North America but some Norwegians consider it useful
Video or Still Photography

Pros:
1) Measurement in field is relatively easy
2) Equipment is relatively affordable
3) Waste feed or feces and bacterial mats sometimes visible
4) US farms are already required to use feed loss monitoring

Cons:
1) Not quantitative, so not really a performance measure
2) Often not directly indicative of infauna health or chemistry
3) Difficult to summarize and interpret
4) Difficult at great depth (open ocean) or in high currents
5) For some species, feces looks very much like waste feed!

Principal tool in hard bottom areas, required in many jurisdictions, but often not scrutinized closely (except Maine)
The above is for northern temperate latitudes. But the approach is repeatable in tropical ecoregions without near as much work as it took previously by establishing background conditions and fine tuning of methodology (e.g., TOC & biogenic carbonates).
Example of Coastal Ecoregions
Benthic effects

Subject of most study & regulation

*Suggested overarching performance standard:*
Maintain aerobic conditions of surficial sediments (top few cm)

*Why and how much?*

*Better for fish: eliminate H₂S flux to water column*

*Better for water column protection: eliminate ammonia flux to water column via “coupled denitrification”*

*Better for infauna: maintain bioturbation and ↑O₂ flux allows for more & diverse populations*

*Reduced nutrient loading to water column and increased nutrient trapping*

*A few centimeters is enough* (See Roger Newell’s presentation)
Water Quality (Column) Effects

• Water column effects include oxygen deficit plume, nitrogen plume, eventual primary productivity or higher trophic level.

• For many cases, not significant compared to flux of these constituents or in terms of spatial effects.

• But potentially cumulative & significant for a large number of farms in highly oligotrophic or very poorly flushed backwaters.

  Suggested goal: to avoid siting in “nutrient sensitive” areas in addition to usual avoidance of special habitats.

• Governmental performance standards vary greatly or are lacking. Examples: coral reef in proximity, limit discharge to very small percentage of N flux.
Nutrient Sensitivity Rating:
Percentage observations
< 0.7 uM DIN ~ 0.01 mg/L-N

From Rensel, J.E. and PTI Environmental 1991 Nutrients and Phytoplankton in Puget Sound USEPA Region X. (Peer reviewed monograph)
Nutrient sensitive zone where commercial net pens or any other large source of N discharge is not approved.
Spatial Considerations for performance monitoring

- Sediment impact zone (SIZ) management (like mixing zone)
- Regulatory endpoints established at some distance from pens
- Inner sampling (less common and less useful, e.g. Maine)
- Effects form a continuous distribution.... So excessive impact under center of pens will be significant at pen perimeter or beyond so it can be redundant to sample all over
Physics Rules! (Biology)

Current Velocity - Percent Frequency

- **High Energy - Erosional**
- **Transitional**
- **Depositional**

**Percent Frequency**

**Current Speed cm/s**

50 cm/s = 1 knot
Cage type: dictates impact zone assessment sampling plan and regulatory approach

Not easy to monitor

Easy to monitor
Example Offshore Current Rose
(current and direction vectors)

First 6 months

Second 6 months
Organic Carbon Enrichment Effects Continuum

Enhancement Zone

~ 30 to 50 m Perimeter

Starting point varies site specifically

Source: Pearson and Rosenberg 1978
Naturally-occurring colonizing species ("biofouling")
This work still in progress, as part of IMTA studies now. Goal is a quantitative mixing model to characterize nutrient flux to key species.
Surf Scoters are declining rapidly in abundance but Puget Sound fish farm surrounds are a well-known refuge and major food source with thousands of bird present every winter.
Final Report:
Beneficial Environmental Effects of Marine Finfish Mariculture

Prepared for:

NOAA National Marine Fisheries Service
National Sea Grant College Program,
Office of Oceanic and Atmospheric Research
Washington D.C.

22 July 2007

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2/ Forster Consulting, Port Angeles

Available on line at NOAA Aquaculture website
Water column and Benthic Effects Simulation Modeling

Qualification:

Modeling not a replacement for monitoring but required by some jurisdictions for permitting (e.g., Scotland) to indicate scale of likely effects and to aid in site configuration.
Potential Uses of Models

- **Government regulators or coastal managers** to assess impacts and effects:
  Is a proposed operational sustainable in terms of achieving limited impact in a steady state basis?

- **Mariculturists** to evaluate potential sites and plan operations:
  Will a candidate site be economically viable as well as environmentally acceptable and how can operations be improved by capitalizing on site-specific conditions?

- **Researchers** to provide a home for their data and means to test and visualize their submodels
Types of Models used in Aquaculture

**One-box**
- Spreadsheet models or simple physics models, e.g., “tidal prism” flushing model
- Simplistic, easy for public to understand, sometimes accurate, often not, many assumptions

**Multi-box: 2 and 3 Dimensional (Coupled)**
- Multiple cells in the grid, side by side (2D) or stacked vertically (3D)
- Requires input from circulation model as inter-box exchange

**Benthic, near-field (e.g., DEPOMOD, MUSMOD, ShellsIM)**
- Biophysical focus on sea or river bottom effect only
- Localized and near to farm

**Geographic Information System (GIS) linked to Aquaculture Model**
- Near or far-field benthic and water column model with companion GIS system
- Three examples including EASY GIS and AquaModel “plug in” combination

**Mainframe 3D fully coupled models**
- Princeton Ocean Model, Finite Volume Coastal Ocean Model, several other
- Suited for future EbM models but expensive, difficult for coastal managers to initiate and use
Example: Physical Modeling Process

Determine boundaries & specify initial water and sediment quality conditions

Divide into modeling grid (vert. & horiz. mesh)

Input water current sub-model & physical processes from empirical data or if using OOS, “data acquisition” updates
DEPOMOD (Scottish origin)

Plot of typical DEPOMOD output showing (left) the location of cages and bathymetry (all scales in metres) and (right) predicted footprint of deposition in g Carbon/m²/d simulating the farm site at peak production. The yellow line indicates the predicted 5gC/m²/d boundary currently used as an Authorization threshold in Pacific Region.
• The only three dimensional GIS for marine applications
• Compatible with other GIS (ESRI Arc-Info)
• Interfaces for models, spreadsheets, databases, and Internet
• Accepts plug in models like AquaModel that we will focus on today
Fish swim respirometer

Fish respiration rate

Fish fecal settling rate

Fish excretion rate

$y = 3200.3x^{-0.5881}$

$R^2 = 0.9304$
Mass Balance Carbon/Nitrogen/Oxygen Metabolism

- Rate of loss of uneaten feed = feed rate – ingestion rate
- Ingestion rate = egestion rate + assimilation rate
- Rate of feces production = egestion rate

Assimilation rate = rate of respiration + rate of growth

- Respiration rate = resting rate (i.e. basal) + active (swimming) + anabolic activity (growth)
- Equations invoke principle of most limit metabolic process
- Assimilation may be limited by fish size, water temperature, oxygen flux, feed rate, “scope for metabolism” approach
Benthic - Pelagic Model Linkages

Simplified particle deposition & consolidation or transport

gas diffusive exchange

Resuspension Zone

Particulate Organic Matter

Sediment to Water Column

NH₄, CO₂, O₂, H₂S

H₂O → aerobic biomass → O₂, CO₂, H₂O → Chemo-autotrophic biomass → CO₂, H₂O → deep RPD “black layer”

H₂S → anaerobic biomass → SO₄

Shallow RPD

Deep RPD
**Examples of Some AquaModel User Controls**

<table>
<thead>
<tr>
<th>Processing Mode</th>
<th>Capture File</th>
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</thead>
<tbody>
<tr>
<td>Replay</td>
<td>C:\PR_3farms_onehalf.cap</td>
</tr>
</tbody>
</table>

### Array

- **Array center/heading (deg):** 10.0550, 65.7711, 210.00
- **Array cell size L/W/D (m):** 52.5, 104.9, 5.0
- **Array dimensions L/W/D:** 51, 31, 6
- **Capture cell 1 L/W/D:** 0, 0, 1
- **Capture cell 2 L/W/D:** 0, 0, 1
- **Capture cell 3 L/W/D:** 0, 0, 1
- **Bottom depth (m):** 30

### Pens

- **Pen:** 1
- **Pen lat/lon/depth (deg.m):** 18.0550, 65.7711, 5
- **Pen size L/W/D (m):** 50.0, 100.0, 5.0
- **Pen fish weight/density (g.kg/m3):** 4000.0, 7.5

### Condition:

- **Water temperature (degC):** 28.0
- **Mixed layer depth sum/win (m):** 30.0, 30.0
- **Tidal period (hrs):** 12.0
- **Max. current velocity (cm/sec):** 8.0
- **Turbulence horz/mixed/strat:** 0.100, 0.050, 0.001
- **Oxygen (mg/L):** 7.00
- **Nitrogen (um):** 0.15

### Operations

- **Sediment oxygen min/max/init (g/m2):** 0.0, 5.0, 1.0
- **Sediment waste min/max/init (g_C/m2):** 0.0, 6.0, 0.0
- **Suspended oxygen min/max/init (g/m3):** 0.0, 3.0, 1.0
- **Suspended waste min/max/init (g_L/m3):** 0.0, 1.0, 0.3
- **Sediment aerobic/anaerobic (g/m3):** 5.0
- **Fecal waste fraction (%):** 25.0
- **Fecal/food sink rates (cm/sec):** 1.00, 9.00
- **Water oxid. rate (%/day):** 1.0
- **Deposition threshold (cm/sec):** 4.5
- **Erosion threshold (cm/sec):** 6.0
- **Erosion rate (g_C/m2/day):** 60.4
Simple Example Snapshot of AquaModel Run

X-Y plots of Nitrogen or oxygen vs. depth

Two of 50 different plots available

Plan (top) view of carbon deposition on the ground
Day 137 Hydrogen sulfide footprint

Day 137 Total organic carbon footprint

Day 137 Aerobic biomass footprint

Day 137 Anaerobic biomass footprint
Hubbs SeaWorld Research Institute Offshore San Diego Project: Example of transitional resuspensional open ocean site
Far Field Example of AquaModel: 20 farms near S. Ca. Bight
### Tabular Output Results Example:

**Under cages or other selectable locations & depths**

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**Within or Under Cage**

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<th>Units→</th>
<th>Flow Velocity</th>
<th>Growth Rate</th>
<th>Fish Biomass</th>
<th>Dissolved Oxygen</th>
<th>Nitrogen</th>
<th>Phytoplankton</th>
<th>Zooplankton</th>
<th>Fecal Carbon</th>
<th>Feed Carbon</th>
<th>Sediment Carbon</th>
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<td>5.24</td>
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<td>0.03</td>
<td>0.06</td>
<td>0.01</td>
<td>0.03</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Model Validation, Tuning, Sensitivity Analyses

- Critical for success, often not performed
- Validation of component submodels or less likely in total
- Tracer experiments
- Perturbation measurements: upstream and downstream example
- Extensive published record as starting point (avoid wheel reinvention), some trends among fish taxa
- All around best database is for salmon, can be adapted to other species after basic bioenergetics inputs
- One or more variables unknown: Sensitivity analyses
Example Validation: Growth Measurements versus AquaModel calculations

Growth Rate Measured and Predicted by % BW Ration

Growth Rate vs Temperature Graph

- 6%
- 3%
- 1.50%
- P 6%
- P 3%
- P 1.5%

Specific Growth Rate (day)

Temperature
Example of Nitrogen and Oxygen Depletion Plume Validation

- DIN anomaly (uM): In Pen, 6 m Downstream, 30 m Downstream
- DO Anomaly (mg/L): In Pen, 6 m Downstream, 30 m Downstream, Ambient
CO$_2$ Production vs. Carbon Deposition

Red = AquaModel projection

Black = Literature
(Findley and Whatling 1997 measurements)
Concluding Comments

• Water column effects are hard to measure because of advection and dilution but large numbers of farms can create problems in some situations.

• Benthic effects are easy to predict for depositional environments but extremely difficult to estimate without simulation models.

• Fish bioenergetics, physical modeling, planktonic and benthic process understanding provided us with the opportunity to develop a model of fish farm operations and environmental impacts.

• When tuned to good site specific circulation data and the growth metabolism of cultured fish, models can provided accurate predictions with minimal effort, reducing the trial and error problems seen in the past.

• Consistent monitoring and numerical performance standards among different ecoregions may not be technically possible in the immediate future due to data gaps and provincial attitudes but it is a goal worth pursuing standardization.
Partners  www.AquaModel.org  (for more information)

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