Observations and modeling of Narragansett Bay nutrient dynamics:

Do we run the west coast offense?

Presenters:
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Rhode Island Coastal Waters: Narragansett Bay & Rhode Island Sound

East Coast *Offense*:

- Nutrients from watershed
- Urbanized
- Higher runoff

West Coast *Offense*:

- Nutrients from shelf
- Lower runoff
Focus on Watershed Nutrients to Narragansett Bay Estuary

River nutrients:
Northern
- Blackstone River
- Pawtuxet River
- Woonasquatucket/Moshas.

Eastern
- Taunton River

KEY PT. SOURCES: WWTFs or waste-water treatment facilities
- Fields Pt. & Bucklin Pt. (NBC)
Connecting Circulation > Nutrients > Water Quality

Chronic Low Oxygen Regions
Red = hypoxia

Seekonk R.
Edgewood Shoal
Greenwich Bay
West Passage

http://www.geo.brown.edu/georesearch/insomniacs/
Utilize a 3-legged stool approach to Coastal circulation

e.g. Edgewood Shoals Region

ROMS Numerical Model
Regional Ocean Modeling System

Scaled Physical Model

Spatial-Temporal Observations
Tilt Current Meters

Circulation Data

Lagrangian Drifters

Ship-mounted ADCP

Bottom-mounted ADCP
20 Years of Bay Data:

Counterclockwise residual flow
Up east, Out west

Impacted embayments
Retention gyres
Reduced flushing
Method 3: Computer Models

Numerical modeling

Regional Ocean Modeling System (ROMS*) is a three-dimensional hydrodynamic model

* Shchepetkin, A. F., and J. C. McWilliams, 2005: The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following coordinates ocean model, Ocean Modelling, 9, 347-404
Input Forcing:
- Tides
- Runoff
- Winds
- Air Temperature
- Water Density (Salt, Temp.)

ROMS Model Solves Equations:
- Conserve Mass
- Momentum
- Conserve Energy / Salt

3. Output:
- 4-D Flow & Salt/Temp. Transport

Today's talk
(a) Chemical Dyes
(b) Ecosystem Processes
ROMS Cases. Terrestrial (East-coast) nutrient dynamics

Case 1

(1) Nutrients as passive chemical dye advection/diffusion only

Dye sources supplying low-DO areas?

- January – September 2010
- River discharge (USGS), Winds (PORTS), Tides (ADCIRC), Atmospheric (reanalysis-NARR), rain (TF Green).

Forcing files detail
- Pawtuxet River nutrients - NBC data.
- Other rivers: empirical flow vs. nutrients model (from UMass model).
- WWTF nutrients (data from plant managers and hypothetical levels)

Case 2

(2) ROMS NPZD Model
N=nutrients, P=phytoplankton, Z=zooplankton, D=detritus

Factors controlling phytoplankton biomass?
Case 1

16 Distinct Dyes
9 Rivers
7 WWTFs

1) How each dye through system?

2) Flushing vs. accumulation?

3) Cost/benefit of WWTF (nutrient) reduction strategies?
Chemical Dye from Fields Pt. WWTF: Focus on upper Providence River

Red = Dimensionless Concentration of 1
Dye from Fields Point WWTF: Transport examples

- Plume in outflow jet
- Plume entrained in shoal gyre
- Plume flushed
(near-surface) Blackstone River Dye: Repeatable Mid-Bay Transport Paths

1. West Passage:
   Weak wind
   SW-ward wind

2. Greenwich Bay Intrusion:
   Seabreeze
   NW-ward wind

3. East Passage
   Strong NE-ward wind
Greenwich Bay?

Nitrogen Contributors to Greenwich Bay: **SPRING HIGH FLOW (+30 days)**

1) Blackstone, 2) Pawtuxet, 3) Fields Pt, 4) Taunton, 5) Internal

From north ——— From east

2. Greenwich Bay

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**Pie Chart**

- **Greenwich Bay**: 23%
- **Blackstone**: 38%
- **Pawtuxet**: 23%
- **Fields PT**: 12%
- **Taunton**: 6%

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**Graph**

**August 1**

**Bottom Dissolved**

- Providence

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**From north**

- Greenwich Bay

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**From east**

- Greenwich Bay
Greenwich Bay?

Nitrogen to Greenwich Bay  
1) Internal,  2) Blackstone, 3) Fields Pt, 4) Pawtuxet

Variable with season, runoff, wind

Late Summer 2010:

Late Summer – August, 2010

Greenwich Bay

Blackstone

Pawtuxet

Fields Pt.

< 1%

16%

9%

5%

12%

55%
Conclusions: Dye Transport Patterns Complex.
Northern sources variable down-bay paths.
Accumulations in impacted areas vary seasonally (winds, runoff)
Counterclockwise residual flow & layered estuarine flow:
   eastern & southern dyes to impacted northern areas.

Near-bottom Taunton Dye
in Providence River

Edgewood Shoals Bottom Water
Second set of ROMS Models: ROMS NPZD Ecosystem Model

Nitrogen not a conservative dye.

\[
\frac{dP}{dt} = \frac{V_m N P}{k_s + N} - mP - I_i Z \quad (1)
\]

\[
\frac{dZ}{dt} = (1 - \gamma)I_i Z - gZ \quad (2)
\]

\[
\frac{dN}{dt} = -\frac{V_m N P}{k_s + N} + mP + gZ + \gamma I_i Z \quad (3)
\]

\[
I_i = R_m (1 - e^{-\frac{\Delta P}{\Lambda P}}) \quad (4)
\]

Multiple runs: Uptake rate, light extinction, grazing, mortality, WWTF levels
Start with focus on bay-wide bloom, June, 2010

Total Nitrogen:  Surface  Reference case:  Vm2.5, KL0.75, ZG1.0

Contours in milli-Mole/m^3 (divide by 75 to get to mg/l).

Transport oscillations:
Northern nutrients
1) down East Passage,
2) down West Passage.
3) pumped into Greenwich Bay

Wind, tide, runoff controls
Total Nitrogen Contours: (near-surface, summer 2010)
Mid-Bay Transport Paths Similar to Dye

Transport oscillations:

Northern nutrients
1) down East Passage,
2) down West Passage.
3) pumped into Greenwich Bay

Wind, tide, runoff controls
Fundamental observation in Bay: TN reduction from Seekonk to Mouth of Providence River

All runs (pre-bloom) have TN match basic observation:

1. 40% reduction Head of Prov. River to Mouth
2. Seekonk 50% higher than upper Prov. River
Phytoplankton Contours: (early summer bloom 2010)
Day 165 (June 14)

Initiate Mid-bay and migrate northward

RED = 20 mM m$^{-3}$
Surface Phytoplankton Contours: (early summer bloom 2010)

Day 165 (June 14)

Movie:

Bloom starts mid-Bay

Moves northward

RED= 20 milli-M m⁻³
Modeled bloom matches a) nutrient magnitudes, 
b) mid-Bay start, c) timing of northward march
Phytoplankton bloom intensity vs. parameters:

1. ecosystem parameters *(uptake, light, death)*
2. environmental factors
3. different WWTF releases levels

Plots from mid-Bay: North Prudence

- Station: NPru
- WWTFs @ 15 mg/mL
- WWTFs @ 5, 3 & 0 mg/mL
Use differential-integrated phytoplankton bloom index to quantify relative sizes of

- environmental factors and
- managed nutrient changes
- NPZD parameters (uptake, light, grazing)

**Difference in Total Bloom Magnitude**

\[ \text{Difference in Integrated Bloom Magnitude over 10 days} = \text{ROMS Case A} - \text{ROMS Case B} \]
Use differential-integrated phytoplankton bloom index to quantify relative sizes of
a) environmental factors and
b) managed nutrient changes
c) NPZD parameters (uptake, light, grazing)

Difference in Total Bloom Magnitude = ROMS Case A - ROMS Case B

If big difference then blooms very sensitive to this parameter

Absolute value
Use differential-integrated phytoplankton bloom index to quantify relative sizes of

a) environmental factors and
b) managed nutrient changes
c) NPZD parameters (uptake, light, grazing)

WWTFs nutrient release levels at 0 mg/L versus 3 mg/L
Variations in Wind Eliminate Greenwich Bay Change Light Extinction Changing Growth Rate Difference in Total Bloom Concentration

Bigger difference 5 mg/L vs. 15 mg/L WWTF releases, \textit{factor of 10}
Higher phytoplankton uptake rate, 15 to 5 mg/l change in WWTF release, bigger impact
Compare changes in applied prevailing wind to a reference case of no-wind.

Natural effect of wind changes has similar impact as 15 to 5 mg/l WWTF change.
Changes in light penetration parameter larger impact on integrated total bloom than managed (e.g. 5mg/l to 3/mg/l) nutrient reductions from WWTFs.
Phytoplankton uptake rate key parameter for integrated total bloom

- Medium Growth Rate
- High Growth Rate
- Variations In Wind
- Changing WWTF Nutrient Outputs
- Change Light Extinction
- Changing Phytoplankton Uptake Rate

Difference in Total Bloom Concentration

- 3 to 0
- 5 to 3
- 15 to 5

Southeastward, Northwestward, Northeastward, Southwestward

Low to Medium, Medium to High
Conclusions:

Order of factors controlling bloom size
1) Ecosystem parameters (growth, light, etc)
2a) Environmental parameters (winds)
2b) 15 to 5 mg/l drop in WWTF releases
3) 5 to 3 mg/l drop in WWTF releases

Relative importance of shelf (RIS) nutrients for Bay ecosystem?

Scott Nixon, first week of work, 
“let’s test how DIN from shelf gets into Bay”
Building RIS Data Sets / Models  *RISG, Endeavor Prog.*

1) 1999-2001 led by Scott Nixon

Coastal Current
- Strong in summer
- Into RIS from SE, exit to SW

Weak interior flow

Summer stratification

RIS to Bay Intrusions!!
1. Colors show 3 deployment sites: Solid line=3m; Dashed=6m

2. Drifters Retained in Vineyard Sound

3. Drifters ride coastal current to Bay
   13 Days

4. What's up, central RIS?

Nixon, Granger, Fulweiler and others
Series of “intensive” cruises (RISG)
Narragansett Bay to RIS (99-01)
Temperature, salinity, nutrient surveys

Average Summer Conditions

North

South

Temperature

DIN

DIN: 7 mg/L

BAY

RIS

T=16°

T=10°
Nixon: “Is deep RIS DIN an important source for Bay?"

1999-2001: 17 Full tide cycle ship-mounted ADCP cruises

Mouth-interface region of Bay – RIS

Winter/summer residual (or subtidal) exchange similar

East Passage ADCP Sub-tidal flow

West Side

East Side

Looking north

3800 meters

1300 meters

35m

Depth, m
1999-2001: 3 moored ADCPs. East Passage, West Passage, RIS

2007: 3 BM-ADCPs East/West Pass.

2008: 2 BM ADCPs RIS

ADCP Shows Wind-driven Intrusion

Northward Inflow

Northward wind

Southwestward wind

Subtidal Flow, cm/s

Days since wind event, 5/20/2000
Two Modes of RIS to Bay Flow  (*Pfeiffer-Herbert et al, 2015*)

1) Mean residual (non-tidal) inflow to East Passage (3-5 cm/s)
2) 5-15 Wind-driven intrusions per summer

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Table 2

Summary of near-bottom exchange event characteristics. Events were defined as periods of near-bottom flow greater than one standard deviation above the mean. Wind velocity associated with events was designated as “favorable” or “unfavorable” by correlation analysis (Fig. 5).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SHS</th>
<th>SHE</th>
<th>SHN</th>
<th>WPL</th>
<th>EPL</th>
<th>EPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Exchange flow” direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold velocity for enhanced exchange flow</td>
<td>2.4 cm s⁻¹</td>
<td>11 cm s⁻¹</td>
<td>3.4 cm s⁻¹</td>
<td>12.8 cm s⁻¹</td>
<td>10.0 cm s⁻¹</td>
<td>12.0 cm s⁻¹</td>
</tr>
<tr>
<td>Number of events</td>
<td>13</td>
<td>15</td>
<td>9</td>
<td>5</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>Events with maximum velocity in bottom half of water column</td>
<td>2 (15%)</td>
<td>10 (67%)</td>
<td>9 (100%)</td>
<td>0 (0%)</td>
<td>10 (91%)</td>
<td>15 (88%)</td>
</tr>
<tr>
<td>Events with near-surface flow at or below average</td>
<td>7 (54%)</td>
<td>5 (33%)</td>
<td>8 (89%)</td>
<td>0 (0%)</td>
<td>4 (36%)</td>
<td>15 (88%)</td>
</tr>
<tr>
<td>Events with rebound (before or after event)</td>
<td>7 (54%)</td>
<td>11 (73%)</td>
<td>6 (67%)</td>
<td>3 (60%)</td>
<td>5 (45%)</td>
<td>9 (53%)</td>
</tr>
<tr>
<td>Events with favorable wind during event and within 6 h prior</td>
<td>5 (38%)</td>
<td>9 (60%)</td>
<td>5 (56%)</td>
<td>1 (20%)</td>
<td>6 (55%)</td>
<td>1 (6%)</td>
</tr>
<tr>
<td>Events with favorable wind during event but unfavorable wind within 6 h prior</td>
<td>6 (46%)</td>
<td>4 (27%)</td>
<td>3 (33%)</td>
<td>3 (60%)</td>
<td>3 (27%)</td>
<td>16 (94%)</td>
</tr>
<tr>
<td>Events with unfavorable wind during and within 6 h before event</td>
<td>2 (15%)</td>
<td>2 (13%)</td>
<td>1 (11%)</td>
<td>1 (20%)</td>
<td>2 (18%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

Please cite this article as: Pfeiffer-Herbert, A.S., et al., Dynamics of wind-driven estuarine-shelf exchange in the Narragansett Bay estuary. Continental Shelf Research (2015), [http://dx.doi.org/10.1016/j.csr.2015.06.003](http://dx.doi.org/10.1016/j.csr.2015.06.003)
Mode 1: "Steady" inflow
1000 CMS
200K Moles DIN per day

Mode 2: Large wind-driven inflow
>7000 CMS
7 million Moles DIN/event
Pump station & ADCPs. Firm up Volume flux & Chemical flux vs. time

West Side

Lower East Passage

East Side

30 m

3 Horse intakes

In-line sensors, pumps, controls

EPSCOR Funding
RISG Funding

Moored ADCPs

7 mg/L?

INFLOW

OUTFLOW

Looking north

Lower East Passage ADCP Sub-tidal flow
ROSA: Ongoing work, ROMS Modeling & Analysis of existing data sets

Supply pathways RIS water/nutrients to Narragansett Bay.

Background/steady intrusions

Wind-induced, large scale intrusions

High energy exchange events (Floyd).
Shelf Intrusions

Persistent trickle from Periphery Current

2-7 day wind events

Quick, Extreme events
1. ADCP under the Newport Bridge during the storm
   a. This is a good test of model performance: captured both the bottom temperature and the vertical structure of the currents.

![Image of Newport Bridge](http://cdn.onlyinyourstate.com/wp-content/uploads/2016/04/Aerial_view_of_Claiborne_Pell_Newport_Bridge_-01-700x501.jpg)

![Diagram of ADCP setup](http://cdn.onlyinyourstate.com/wp-content/uploads/2016/04/Aerial_view_of_Claiborne_Pell_Newport_Bridge_-01-700x501.jpg)

- $H = 40 \text{ m}$
- $\Delta z = 2 \text{ m}$

The ROMS model
The ROMS model

- RIVERS
- WIND
- HEAT, FRESHWATER
- TIDES + ADCIRC
- NON-TIDAL VEL. & SSH
Bottom temperature time series

Storm landfall

4°C drop
Cool, high-DIN shelf-water?
Bottom temperature: data vs. model

Bottom temperature at ADCP

- Observations
- fsg31 stratified
Quantifying post-storm intrusion: data only

Assessing model skill

Cumulative volume/meter for bottom 20 m at ADCP

ADCP Observations

Assessing model skill
Quantifying post-storm intrusion: data vs. models

Assessing model skill

Cumulative volume/meter for bottom 20 m at ADCP

ADCP Observations

ROMS No Stratification
Quantifying post-storm intrusion: data vs. models

Assessing model skill
Quantifying post-storm intrusion: data vs. models

Assessing model skill

The barotropic (constant-density) model does not predict the strong shelf-water inflow.
Drifter movie 2: Effects of Stratification
Density cross-sections
Drifter movie 3: Storm vs. No Storm
Estimated Input Volume for the 4 days following Floyd:

Rivers: $5 \times 10^7 \text{ m}^3$

East Passage: $5 \times 10^8 \text{ m}^3$

(USGS Data)

(ROMS model)
Bottom temperature time series

Storm landfall
ADCIRC operational model: Forecasting inundation from Irma
ADCIRC operational model: Forecasting inundation from Irma

This ocean model is invaluable for informing evacuations but its simplified physics can’t predict nutrient transports or ecosystem impacts.
Hazardous Chemical spills

a. **Extent of oil spills from Hurricanes Katrina and Rita is still being assessed**

### Katrina and Rita Oil Spills

Hurricanes Katrina and Rita caused 540 separate oil spills throughout the Gulf Coast. A look at the biggest of those spills:

<table>
<thead>
<tr>
<th>Company</th>
<th>Oil spilled IN GALLONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass Enterprises Production Co. (Cox Bay)</td>
<td>3.78 million</td>
</tr>
<tr>
<td>Shell (Pilottown)</td>
<td>1.05 million</td>
</tr>
<tr>
<td>Chevron (Empire)</td>
<td>991,000</td>
</tr>
<tr>
<td>Venice Energy Services Co. (Venice)</td>
<td>840,000</td>
</tr>
<tr>
<td>Murphy Oil Corporation (Meraux)</td>
<td>819,000</td>
</tr>
<tr>
<td>Bass Enterprises (Pointe a la Hache)</td>
<td>461,000</td>
</tr>
<tr>
<td>Chevron (Port Fourchon)</td>
<td>53,000</td>
</tr>
<tr>
<td>Shell Pipeline Oil (Nairn)</td>
<td>13,440</td>
</tr>
<tr>
<td>Sundown Energy (West Potash)</td>
<td>13,000</td>
</tr>
<tr>
<td>Numerous other small spills</td>
<td><strong>About 3 million</strong></td>
</tr>
<tr>
<td><strong>TOTAL:</strong> 11 million</td>
<td></td>
</tr>
</tbody>
</table>

Sources: Former LSU energy researcher in Oceanography magazine, NOAA

[THE TIMES-PICAYUNE](http://www.nbcnews.com/id/10838641/ns/us_news-katrina_the_long_road_back/t/oil-company-katrina-spill-victims-got-r/)
2. Nutrient intrusions, plankton blooms, hypoxia
   a. Roman et al. (2006) “Chesapeake Bay Plankton and Fish Abundance Enhanced by Hurricane Isabel Hurricane”
   b. Li et al. (2006) “Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay”
1. **Goal:** modeling storm events as realistically as possible.

2. Presenting results from a regional 3D baroclinic modeling that is forced by a 2D storm surge model.
   a. Find that even under strong winds, baroclinic (stratification-driven) effects are critical.

3. Argue that this model is well-suited for studying water mass exchanges.
   a. Volume of shelf-water input on order 10x greater than sum of all rivers.
Hurricane Floyd

1. Catastrophic flooding in eastern US, particularly North Carolina
   a. 15’ storm surge in Long Beach, NC
2. 11” of rain in parts on New England
3. RI experienced increased river flows but minimal storm surge and only about 3” of rain.

https://www.weather.gov/images/mhx/19990916/1rain1.jpg
Shouldn’t vertical mixing lead to *warmer* bottom water?
Sea surface height and northward deep velocity

Assessing model skill