Estuary Dynamics and Implications

Drew Lucas
Scripps Institution of Oceanography
ajlucas@ucsd.edu
Andrew J. (Drew) Lucas  
Scripps Institution of Oceanography

Platforms and sensors for upper ocean research

- ocean boundary layer physics
- coastal oceanography
- effluent dispersal
- bio-physical interactions

ajlucas@ucsd.edu
Definitions...
Definitions…

An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.
Definitions…

An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.
Definitions…

An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.

Estuaries are thus regions of property exchange between the continent and the ocean.
Definitions…

An *estuary* is a semi-enclosed region influenced by both *fresh* water from the land and *salty* water from the sea.

Estuaries are thus regions of *property exchange* between the continent and the ocean.
An **estuary** is a semi-enclosed region influenced by both **fresh** water from the land and **salty** water from the sea.

Estuaries are thus regions of **property exchange** between the continent and the ocean.

The **unique dynamics** of estuaries control property exchange and transport and thus are critical to pollutant dispersal.
Definitions…

An *estuary* is a semi-enclosed region influenced by both *fresh* water from the land and *salty* water from the sea.

Estuaries are thus regions of *property exchange* between the continent and the ocean.

The *unique dynamics* of estuaries control property exchange and transport and thus are critical to pollutant dispersal.
Definitions…

An *estuary* is a semi-enclosed region influenced by both *fresh* water from the land and *salty* water from the sea.

Estuaries are thus regions of *property exchange* between the continent and the ocean.

The *unique dynamics* of estuaries control property exchange and transport and thus are critical to pollutant dispersal.

Estuaries provide many important *ecosystem services*, including habitat/nurseries for commercially valuable species, improve coastal water quality, support tourist actives, form the basis of many major shipping lanes.
Motivations…

Many of the largest coastal cities are located where rivers meet the sea. Estuaries are major routes of transport and are often heavily influenced by human activities.
Motivations...

Estuaries often receive intentional and unintentional discharge of effluent (sewage), industrial waste, storm water, and other pollutants.

“After Blaze, Sewage Floods City Rivers” – New York Times 07/22/2011
Motivations…

Many commercially valuable fish, shrimp, crab species, etc. live or breed in estuaries. Also home to many birds and marine mammals. Human activities include fishing and tourism.
An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.
Akwidaa Estuary, Western Region, Ghana
An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.

Akwidaa Estuary, Western Region, Ghana
An estuary is a semi-enclosed region influenced by both fresh water from the land and salty water from the sea.

Akwidaa Estuary, Western Region, Ghana
The river water is fresh and the sea water is salty. What happens when the river water encounters the sea water?

*The unique dynamics* of estuaries control property exchange and transport and thus are critical to pollutant dispersal.

Estuaries are thus regions of *property exchange* between the continent and the ocean.
Schematic estuaries: Vertically homogenous

Fresh (0 g/kg)

S1 < S2 < S3 < S4 < S5 < S6

Salt (35 g/kg)

“Well-mixed estuary”

LAND

The Hudson River Estuary, New York City, USA

SEA
Schematic estuaries: Vertically homogenous

“Well-mixed estuary”

\[ S_1 < S_2 < S_3 < S_4 < S_5 < S_6 \]

The Hudson River Estuary, New York City, USA

The Hudson River Estuary, New York City, USA
Schematic estuaries: Vertically stratified

“Salt wedge estuary”

The Rio de la Plata, Argentina

S1 < S2 < S3 < S4
Schematic estuaries: Vertically stratified

“Salt wedge estuary”

The Rio de la Plata, Argentina

S1 < S2 < S3 < S4
Newton’s 2nd Law recast for fluids (the Navier - Stokes equation)

\[
\frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F}
\]
Newton’s 2nd Law recast for fluids (the Navier - Stokes equation)

\[
\frac{D\mathbf{u}}{Dt} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \mathbf{g} + \mathbf{F}
\]

Acceleration (local + nonlinear terms)
Newton’s 2nd Law recast for fluids (the Navier - Stokes equation)

\[ \frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F} \]

Acceleration (local + nonlinear terms)
Rotation
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
\frac{D\mathbf{u}}{Dt} + 2\Omega \times \mathbf{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \mathbf{g} + \mathbf{F}
\]
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
\frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_0} \nabla p + \frac{\rho}{\rho_0} \vec{g} + \vec{F}
\]

- **Acceleration** (local + nonlinear terms)
- **Rotation**
- **Pressure gradient**
- **Buoyancy**
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
\frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F}
\]

- **Acceleration** (local + nonlinear terms)
- **Rotation**
- **Pressure gradient**
- **Buoyancy**
- **External forces** (wind, friction, tidal, etc)
Newton’s 2nd Law recast for fluids (the Navier - Stokes equation)

\[ \frac{D\vec{u}}{Dt} + \nabla p = -\rho \vec{g} + \rho F \]

- Acceleration (local + nonlinear terms)
- Rotation
- Pressure gradient
- Buoyancy
- External forces (wind, friction, tidal, etc)

HELP THIS IS TOO COMPLICATED!!!! WHAT DO WE DO?
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
\frac{D\mathbf{u}}{Dt} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \mathbf{g} + \mathbf{F}
\]

- **Acceleration** (local + nonlinear terms)
- **Pressure gradient**
- **Rotation**
- **Buoyancy**
- **External forces** (wind, friction, tidal, etc)
Newton's 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
\frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F}
\]

Acceleration (local + nonlinear terms)
Rotation
Pressure gradient
Buoyancy

Assume *steady state*, *neglect rotation*, *hydrostatic* and *spatial variability* only in x (i.e. y-, z- uniform)

External forces (wind, friction, tidal, etc)
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[ + 2\Omega \times \mathbf{u} = -\frac{1}{\rho_o} \nabla p + \rho \mathbf{g} + \mathbf{F} \]

Acceleration (local + nonlinear terms)
Pressure gradient
Rotation
Buoyancy

Assume *steady state*, *neglect rotation*, *hydrostatic* and *spatial variability* only in x (i.e. y-, z- uniform)

External forces (wind, friction, tidal, etc)
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[
0 = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \mathbf{g} + \mathbf{F}
\]

**Acceleration**
(local + nonlinear terms)

**Pressure gradient**

**Rotation**

**Buoyancy**

Assume *steady state*, *neglect rotation*, *hydromstatic* and *spatial variability* only in $x$ (i.e. $y$-, $z$- uniform)

**External forces** (wind, friction, tidal, etc)
Newton's 2nd Law recast for fluids (the Navier - Stokes equation)

\[ 0 = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\rho}{\rho_0} \vec{g} + \vec{F} \]

- **Acceleration** (local + nonlinear terms)
- **Pressure gradient**
- **Rotation**
- **Buoyancy**

Assume *steady state, neglect rotation, hydrostatic* and *spatial variability only in x (i.e. y-, z- uniform)*

*External forces* (wind, friction, tidal, etc)
Newton’s 2nd Law recast for fluids
(the Navier - Stokes equation)

\[ 0 = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \vec{F} \]

**Acceleration** (local + nonlinear terms)

**Pressure gradient**

**Rotation**

**Buoyancy**

Assume *steady state*, *neglect rotation*, *hydrostatic* and *spatial variability* only in *x* (i.e. *y-, z- uniform*)

External forces (wind, friction, tidal, etc)
Newton’s 2nd Law recast for fluids (the Navier - Stokes equation)

\[ 0 = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{1}{\rho_0} \frac{\partial \tau_x}{\partial z} \]

**Acceleration** (local + nonlinear terms)  
**Pressure gradient**

**Rotation**

Assume **steady state**, **neglect rotation**, **hydrostatic** and **spatial variability** only in \( x \) (i.e. \( y-, z- \) uniform)

**Buoyancy**

**External forces** (wind, friction, tidal, etc.)
An idealized estuary:

\[ \eta \]

\[ S_R = 0 \text{ g/kg} \]

\[ S_o = 35 \text{ g/kg} \]

\[ \frac{\partial p}{\partial x} = \frac{\partial \tau_x}{\partial z} \]

Details: the pressure gradient depends on both the sea surface slope (\( \eta \)) and the vertical density gradient and the frictional term is really complicated.
Idealized, tidally averaged, partially mixed estuary

Steady state: $Q_R + Q_2 = Q_1$
Idealized, tidally averaged, partially mixed estuary

\[ \frac{\partial \rho}{\partial z} \]

\[ \frac{\partial u}{\partial z} \]

Steady state: \( Q_R + Q_2 = Q_1 \)
Idealized, tidally averaged, partially mixed estuary

Richardson Number (Ri) = \[
- \frac{g \frac{\partial \rho}{\partial z}}{\left(\frac{\partial \vec{u}}{\partial z}\right)^2} \rho_o \frac{\partial \rho}{\partial z}
\]

Steady state: \( Q_R + Q_2 = Q_1 \)
Idealized, tidally averaged, partially mixed estuary

Richardson Number (Ri) = \[ \frac{N^2}{S^2} \]

Steady state: \( Q_R + Q_2 = Q_1 \)
What happens to the steady state picture if we add tides?

Akwidaa Estuary, Western Region, Ghana
Interaction between the river flow and the tidal velocities

- Beginning of Ebb -

Assume initially $u = 0$ & no stratification

- Beginning of Ebb -

RIVER → OCEAN

$\eta$

velocity

$s_1 < s_2 < s_3 < s_4 < s_5$

salinity

fresh → → → → salty
Interaction between the river flow and the tidal velocities

- Early Ebb -

FLOW ENHANCES THE STRATIFICATION

Ri > 1

Velocity: $s_1 < s_2 < s_3 < s_4 < s_5$

Salinity: fresh → → → → salty
Interaction between the river flow and the tidal velocities

- Max Ebb -

The enhanced stratification suppresses mixing

\[ \eta \sim 1 \]
Interaction between the river flow and the tidal velocities

- Late Ebb -

RIVER → OCEAN

velocity: $s_1 < s_2 < s_3 < s_4 < s_5$

salinity: fresh → → → salty

$\eta$ - Late Ebb -

$Ri > 1$

Ebb → Flood

time →
Interaction between the river flow and the tidal velocities

- Beginning of Flood -

RIVER → OCEAN

velocity: $s_1 < s_2 < s_3 < s_4 < s_5$

salinity: fresh → → → salty

Ri > 1

Ebb
Flood

time →
Interaction between the river flow and the tidal velocities

- Early Flood -

Flow now works to tilt isopycnals back upright

REDUCES STRATIFICATION
Interaction between the river flow and the tidal velocities

- Max Flood -

Stratification is minimal during flood

Turbulent mixing of momentum is enhanced

\[ \text{Ri} \ll 1 \]
Interaction between the river flow and the tidal velocities

- Late Flood -

RIVER $\rightarrow$ OCEAN

velocity $s_1 < s_2 < s_3 < s_4 < s_5$

salinity fresh $\rightarrow$ salty

$\eta$- Late Flood -

$\eta$ $\rightarrow$

Ri $\ll 1$

Ebb $\rightarrow$ Flood

time $\rightarrow$
Interaction between the river flow and the tidal velocities

- Back to the Beginning of Ebb -

\[ \eta \]

\[ s_1 < s_2 < s_3 < s_4 < s_5 \]

velocity

salinity

fresh \rightarrow \rightarrow \rightarrow \rightarrow \text{ salty}

**Ri \ll 1**
Estuary Classification

- **salt-wedge**
- **weakly stratified**
- **strongly stratified**
- **well-mixed**

The diagrams illustrate the different types of estuaries based on their mixing characteristics.
Estuary Classification

River flow/Estuary area

Tidal mixing

Fr$_f$

Salt wedge

Partially mixed

Well mixed

Strongly stratified

SIPS

Mississippi River

Fraser River

Chang Jiang River

Merrimack River

Elbro River

Amazon River

Chesapeake Bay

San Francisco Bay

Narragansett Bay

Puget Sound

Baltic Sea

Long Island Sound

Fjord

Puget Sound

Bu

Time-dependent salt wedge
An example of biological effects of estuarine processes: Spawning of the Whitemouth Croaker in the Rio de la Plata

An example of biological effects of estuarine processes: Spawning of the Whitemouth Croaker in the Rio de la Plata

Bonus question:
River plumes— What is happening here?
Sampling an estuary: What do you need to know?

1) Vertical gradients in temperature, salinity, and currents

2) Horizontal gradients in T, S, and currents

3) Time variability in T, S, and currents

4) Vertical, lateral, and time distribution of mixing

5) River input and wind field
Sampling an estuary: What do you need to know?

1) Vertical gradients in temperature, salinity, and currents
2) Horizontal gradients in T, S, and currents
3) Time variability in T, S, and currents
4) Vertical, lateral, and time distribution of mixing
5) River input and wind field
Sampling an estuary: What do you need to know?
Sampling an estuary: How?

Horizontal and vertical scales are small. You need **specialized instrumentation that samples quickly.**

Profiling mooring:
- T, S, oxygen, currents, turbulence resolved in **time**

Small boat and kayak profiling:
- T, S, oxygen currents, turbulence resolved in **space**
Small boat and kayak profiling:
Small boat and kayak profiling:
Small boat and kayak profiling:
Small boat and kayak profiling:

Movie removed
Small boat and kayak profiling:

Movie removed
Small boat and kayak profiling:

Movie removed
Small boat and kayak profiling:

Movie removed
The Wirewalker system uses energy from ocean surface waves to drive a profiling body vertically.

Rapid profiling at zero energy cost.

Battery power conserved for onboard instrumentation.

Large field-modifiable payload, indefinite profiling, low cost, simple and robust mechanical design.

>400K cycles and ~20,000 km of Wirewalker profiles in the global ocean in the past 10 years.
The Wirewalker system uses energy from ocean surface waves to drive a profiling body vertically.

Rapid profiling at zero energy cost.

Battery power conserved for onboard instrumentation.

Large field-modifiable payload, indefinite profiling, low cost, simple and robust mechanical design.

>400K cycles and ~20,000 km of Wirewalker profiles in the global ocean in the past 10 years.
The Wirewalker system uses energy from ocean surface waves to drive a profiling body vertically. Rapid profiling at zero energy cost. Battery power conserved for onboard instrumentation. Large field-modifiable payload, indefinite profiling, low cost, simple and robust mechanical design. >400K cycles and ~20,000 km of Wirewalker profiles in the global ocean in the past 10 years.

The Scripps Institution of Oceanography Wirewalker Wave-powered profiler
The Wirewalker system uses energy from ocean surface waves to drive a profiling body vertically. Rapid profiling at zero energy cost. Battery power conserved for onboard instrumentation. Large field-modifiable payload, indefinite profiling, low cost, simple and robust mechanical design. >400K cycles and ~20,000 km of Wirewalker profiles in the global ocean in the past 10 years.

The Scripps Institution of Oceanography
Wirewalker Wave-powered profiler
Sampling an estuary: How?

Get a toolkit appropriate to the problem.

Choose the simplest possible sampling scheme that gives the sampling characteristics you require.

Repeat until you can’t stand it. And then repeat some more.
Sampling an estuary: boat
Sampling an estuary: boat
Sampling an estuary: boat
Sampling an estuary: Wirewalker
Sampling an estuary: Wirewalker

Salinity

Depth (m)

Time (h)
The End
Estuary categorization:

**Geological:**
- Coastal plain
- Bar-built
- Delta system
- Tectonic
- Fjords

**Hydrodynamical:**
- Salt-wedge
- Fjord
- Slightly Stratified
- Vertically Mixed
- Freshwater