Estuarine transport time scales

Fernando Andutta\textsuperscript{1}
Eric Wolanski\textsuperscript{1, 2}

\textsuperscript{1} James Cook University
\textsuperscript{2} Australian Institute of Marine Science
Townsville, Australia
The water transport time scale is important because it controls the estuarine ecosystem. It includes a waterborne ecosystem (the blue box) that is moving with the water currents, to be flushed out at a rate = water transport time scale.

It comprises also suspended sediment + a benthos and bottom dwelling animals.

The waterborne ecosystem (blue box) is advected seaward, thus remaining only in transient contact with the substrate and the tidal wetlands.

At the same time it is subject to increasing salinity as a result of mixing.
Definition of time scales

Since the 1950s, estuarine physicists (e.g. Ketchum, 1950; Cameron & Pritchard, 1963; Dyer, 1973) have used the term ‘residence time’ of water to express many different concepts, such as
- the time it takes to flush an estuary,
- the time that river water spends in an estuary,
- the time it takes for the estuarine water to be renewed
- the time it takes for pollutants to decrease by a factor of 1/e
- the time it takes for river water to exit an estuary
- …

These definitions are confusing because
- they are not addressing the same process;
- therefore they yield different results;
- there is still some confusion amongst oceanographers;
- and this confusion is even more widespread amongst biologists and ecologists.
Physicists have now defined clearly the transport time scales,
(1) the renewal time.
(2) the flushing time,
(3) the age,
(4) the residence time,
(5) the exposure time

(Monsen et al., 2002; Delhez, 2006; Delhez & Deleersnijder, 2006)
Definition of the residence time

To avoid misunderstandings and even erroneous conclusions, it is important to introduce precise definitions and to use them with care.

(Bolin and Rodhe, Tellus 25, 1973)

\[
\begin{align*}
\text{age} &= t - t_{in} \\
\text{residence time} &= t_{out} - t \\
\text{transit time} &= t_{out} - t_{in}
\end{align*}
\]
Flushing time:
All the water particles in the estuary are marked by a virtual tracer in a model. They are followed over time by a numerical model. The flushing time is calculated as the time it takes for the average tracer concentration to decrease to $1/e$ (~0.37) of its initial concentration (Ketchum, 1950; Dyer, 1973).

Example: Maunalua Bay. Hawaii.
Question: what to do with water that leaves the estuary and then returns?

Examples:

4 systems on the Great Barrier Reef

Andutta et al. (subm.)
Residence time vs exposure time

- Particles that left the domain can enter it again at some later time. This can be taken into account by means of the exposure time, i.e. the time spent in the domain of interest — whereas the residence time is the time needed to leave it for the first time.

The difference between exposure time and residence time is due to the **coastal boundary layer.**

- buoyant river plume which favour \( T_{\text{residence}} = T_{\text{exposure}} \)
- vertically well mixed waters in shallow waters. These favour \( T_{\text{residence}} < T_{\text{exposure}} \)
Conservation equation: for constant $u$ and $K$:
$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = K_x \frac{\partial^2 C}{\partial x^2}$$

Advective time scale: $T_a = \frac{L}{u}$

Diffusive time scale: $T_d = \frac{L^2}{K_x}$

Peclet number = $T_d/T_a = \frac{uL}{K_x}$

For residence time: $C=0$ at $x=0$ and $x=L$ for exposure time $C=0$ at $x=\infty$

Average residence time $\theta = T_a \left[0.5 + \frac{1}{\exp(P_e) - 1} - \frac{1}{P_e}\right]$  

Average exposure time $\Theta = T_a \left[0.5 + \frac{1}{P - \{1 - \exp(-P_e)\} / P_e^2}\right]$  

(Delhez & Deleersnijder, 2006)
This leads to calculating the **return coefficient** $r$, i.e. the probability that a water particle leaving the estuary will return in the estuary

$$r = \frac{(\text{exposure time} - \text{residence time})}{\text{exposure time}} = \frac{(\Theta - \theta)}{\Theta}$$

(Delhez & Deleersnijder, 2006)
However the CART and LOICZ models assume constant $u$ and $K_x$.

How bad is that assumption?

Answer: pretty bad as it assumes constant width and constant depth!
Renewal time

If water is removed at a daily rate $V_1$ (m$^3$ day$^{-1}$) from an estuary of water volume $V$, then the renewal time $T_{\text{renewal}} = V/V_1$

**Examples:**

- *The tidal prism box model* (side view)

- *The gravitational circulation box model* (side view); it neglects tidal mixing

- *The LOICZ box model for a vertically well-mixed estuary* (plan view). It accommodates river flow and tidal mixing
The LOICZ box model

LOICZ time scale = renewal time scale, but it is called, wrongly, a residence time.

The model has been applied to > 200 estuaries worldwide.

(Smith et al., 2005 and 2010; Crossland et al., 2005; Swaney et al., 2011)
The water inflow rate in the estuary is $Q_r$. This same water flux leaves the estuary + rainfall-evaporation+groundwater.

Coastal water with salinity $S_o > S_e$ diffuses into the estuary.

**Salt balance equation:** advective export of salt $S = \text{diffusive import of salt}$

(K$_x$ = eddy diffusion coefficient)

$$Q_r <S> = K_x A \frac{dS}{dx} = K_x A \Delta S \Delta x = Q_d \Delta S$$

where

$$Q_d = K_x A/\Delta x$$

is the equivalent water inflow from the sea; it is not an advective inflow, it is a diffusive inflow.

The LOICZ method assumes

$$\Delta S = (S_o - S_e)$$

where

$$<S> = 0.5 (S_o + S_e)$$

Thus the renewal time $T_r$

$$T_r = V / (Q_r + Q_d)$$
Comparison between
-renewal times (LOICZ),
-residence and exposure times (CART),
-residence time from numerical models

There are large differences between the estimates!
Biologists ask for estimates of residence times for hundreds of estuaries worldwide, but very few of them (maybe 50?) were modeled using numerical models.

For instance in tropical Queensland only 4 ‘large’ estuaries were modeled out of >50.

While numerical models are more reliable to estimate the residence time, there are not enough oceanographers to model all the estuaries for the biologists.

Therefore box models are still extensively used, e.g. the LOICZ model has been applied to > 200 estuaries worldwide.
How do residence times affect the fate of nutrients in an estuary?

The LOICZ box model investigates the budget of dissolved inorganic nutrient (Y, namely of DIC, DIN and DIP).

If nutrients were conservative (such as salinity) then the net budget
\[ \Delta Y = (\text{IN-OUT}) = 0. \]

But they are not conservative (i.e. they are consumed or released by the biology in the estuary); hence \( \Delta Y \neq 0 \); this is the Net Ecosystem Metabolism (NEM).

Swaney et al. (2011)
The method calculates where the nutrients go:

1. It calculates from the field data the **observed** \( \Delta \text{DIN}_{\text{obs}} \) and \( \Delta \text{DIP} \).

2. It uses the observed \( \Delta \text{DIP} \) to compute NEM:
   
   \[
   \text{NEM} = \text{organic production} - \text{respiration} = p - r = - \Delta \text{DIP} \, 106:1
   \]

3. Assuming stoichiometry C:N:P=106:16:1, it calculates the expected \( \Delta \text{DIN}_{\text{exp}} \)

   \[
   \Delta \text{DIN}_{\text{exp}} = \Delta \text{DIP} \, 16:1
   \]

   and the difference between expected and observed \( \Delta \text{DIN} \)

   \[
   [\text{Nfix} - \text{denit}] = \Delta \text{DIN}_{\text{obs}} - \Delta \text{DIN}_{\text{exp}}
   \]

Wolanski and Swaney (in prep.)
The muddy (new) LOICZ box model also takes into account the sequestering of nutrients on the suspended fine sediment.
**DIP and DIN balance**

Example of the Fitzroy Estuary, Queensland, in the dry season

No mud: $\Delta \text{DIP} = 11.2 \text{ mole/m}^2/\text{day (net loss)}$

With mud: $\Delta \text{DIP} = -7.2 \text{ mole/m}^2/\text{day (net gain)}$

No mud: $\Delta \text{DIN} = +139 \text{ mole/m}^2/\text{day (net loss)}$

With mud: $\Delta \text{DIN} = -167 \text{ mole/m}^2/\text{day (net gain)}$

$(p-r) = -1200 \text{ mole/m}^2/\text{day (no mud)}$

$= +760 \text{ mole/m}^2/\text{day (with mud)}$

$(\text{Nfix-denit})$

$= -40 \text{ mole/m}^2/\text{day (no mud)}$

$= -52 \text{ mole/m}^2/\text{day (with mud)}$
10. Conclusions and recommendations

• There is still some confusion in the literature about estuarine time scales.

• There are still difficulties in measuring/calculating these time scales.

• The result for water transport time scale can be sensitive (a factor of ~2) to which time scale is chosen.

• Box models are here to stay because there are more estuaries and ecologists than there are physical oceanographers to build detailed models of each estuary.

• Great care is needed to apply water transport time scales to estimate the fate of nutrients in estuaries, to avoid large errors.

• The fate of nutrients is very sensitive (a factor of ~10 and even a change of sign) on the mud in suspension.