# Estuaries: Classification and Mixing Processes

OCN 623 – Chemical Oceanography

20 March 2014

# Outline

- River-water *vs.* sea-water concentrations
- Definitions of types of estuaries
- Mixing curves
- The mid-estuary turbidity maximum
- Submarine groundwater discharge

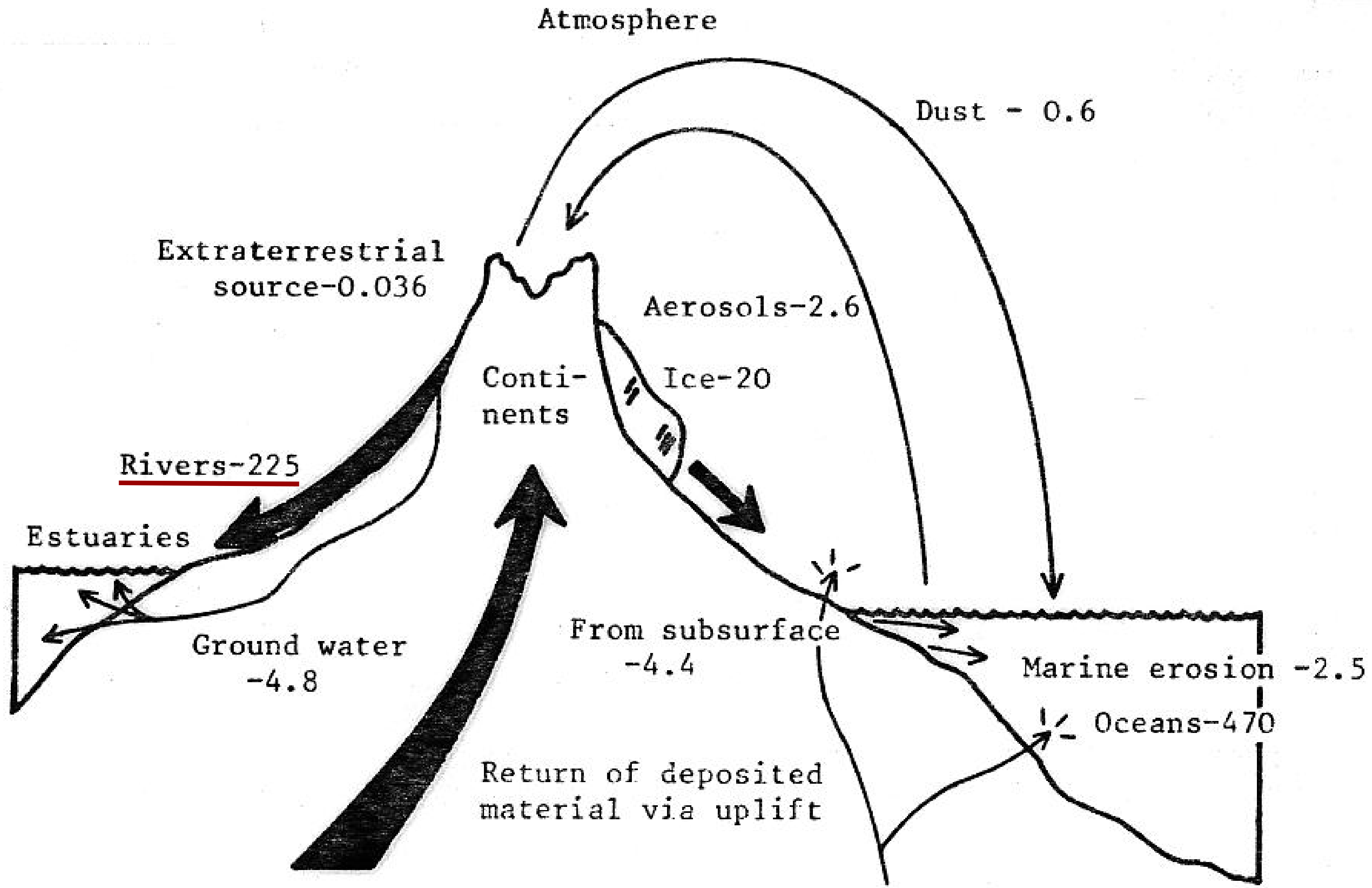



FIG. 41.1. Total masses of materials transported to and leaving the oceans by various agencies (from Garrels and Mackenzie, 1971). Mass values are (per year) $10^{14}$ g, except for the total dissolved solids in the oceans which are in units of $10^{20}$ g.

# River-water and Sea-water Concentrations

*Average abundances of nutrient and major ions in river-water and sea-water*[a]

| Element | | Concentration in river-water (µg l⁻¹) | Concentration in sea-water[b] (µg l⁻¹) |
|---|---|---|---|
| Cl | | $8 \times 10^3$ | $1{\cdot}987 \times 10^7$ |
| S | | $3{\cdot}7 \times 10^3$ | $9{\cdot}28 \times 10^5$ |
| Br | | 20 | $6{\cdot}8 \times 10^4$ |
| F | | 100 | $1{\cdot}4 \times 10^3$ |
| B | rw << sw | 10 | $4{\cdot}5 \times 10^3$ |
| Na | | $9 \times 10^3$ | $11{\cdot}05 \times 10^6$ |
| Mg | | $4{\cdot}1 \times 10^3$ | $1{\cdot}326 \times 10^6$ |
| Ca | | $1{\cdot}5 \times 10^3$ | $4{\cdot}22 \times 10^5$ |
| K | | $2{\cdot}3 \times 10^3$ | $4{\cdot}16 \times 10^5$ |
| Sr | | 50 | $8{\cdot}5 \times 10^3$ |
| N | | $2{\cdot}5 \times 10^2$ | 500 |
| P | rw ≈ sw | 20 | 70 |
| Si | | $6{\cdot}1 \times 10^3$ [c] | 1000 |

Nutrients are different! (N, P, Si)

[a] Data from Riley and Chester (1971).
[b] Salinity = 35‰.
[c] Data from Livingstone (1963).

# River-water / Sea-water Ion Ratios

**TABLE 21.12**
Comparison of the Major Ion Ratios in River Water and Seawater

| *Ion Ratio* | *River Water* | *Seawater* |
|---|---|---|
| $Na^+/K^+$ | 2.5 | 50 |
| $Na^+/Mg^{2+}$ | 4 | 5 |
| $Na^+/Ca^{2+}$ | 2 | 0.2 |
| $K^+/Mg^{2+}$ | 2 | 0.1 |
| $K^+/Ca^{2+}$ | 4.5 | 10 |
| $Ca^{2+}/Mg^{2+}$ | 9 | 1 |

Two major factors:

- $Na^+/K^+$ difference reflects lower affinity of marine rocks for sodium, as compared to potassium (ocean is a is less effective sink for sodium)

- $Ca^{2+}/Mg^{2+}$ difference reflects preferential removal of calcium in the ocean as biogenic calcite (ocean is a is more effective sink for calcium)

# Definitions of “Estuary”

Two major components involved:

- Transition from fresh (river) water to saline (ocean) water
- Tidal influence

One definition:

> “An estuary is a semi-enclosed coastal water body that extends to the effective limit of tidal influence, within which sea water is significantly diluted with freshwater from land drainage”

- Estuarine ecosystems includes:

  - The river channel, to the maximum upstream extent of tidal influence

  - The adjacent coastal waters, to the maximum extent of freshwater flow

  - Salt marshes and tidal flats that develop along the shore line, built up from riverine sediments deposited as river flow rate slows at sea level; subject to daily tidal inundation

- Estuaries are zones of mixing, displaying strong salinity gradients from land to sea

# Water Movement in Estuaries

- River flow is essentially unidirectional
- As river water meets the sea, tidal oscillation introduces a bi-directional ("in-out") component to flow
  - This bi-directionality may be throughout the water column (well-mixed estuary)
  - Or there may be predominantly surface outflow and deep inflow (salt-wedge estuary)

# River-dominated Estuary

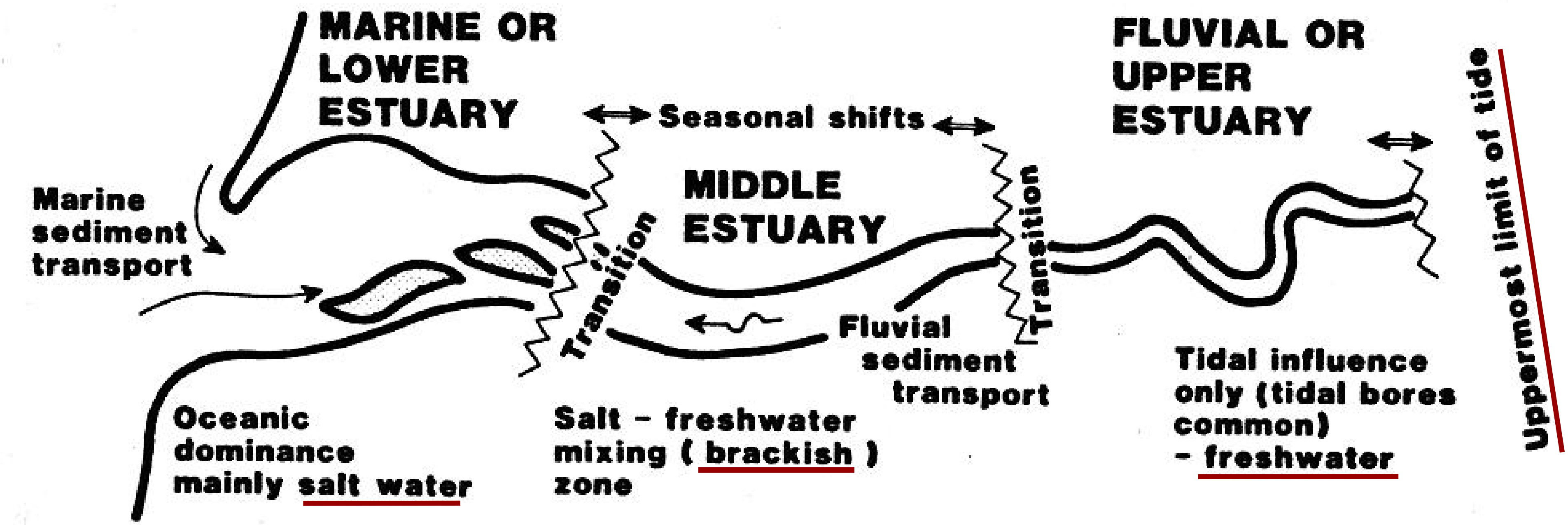
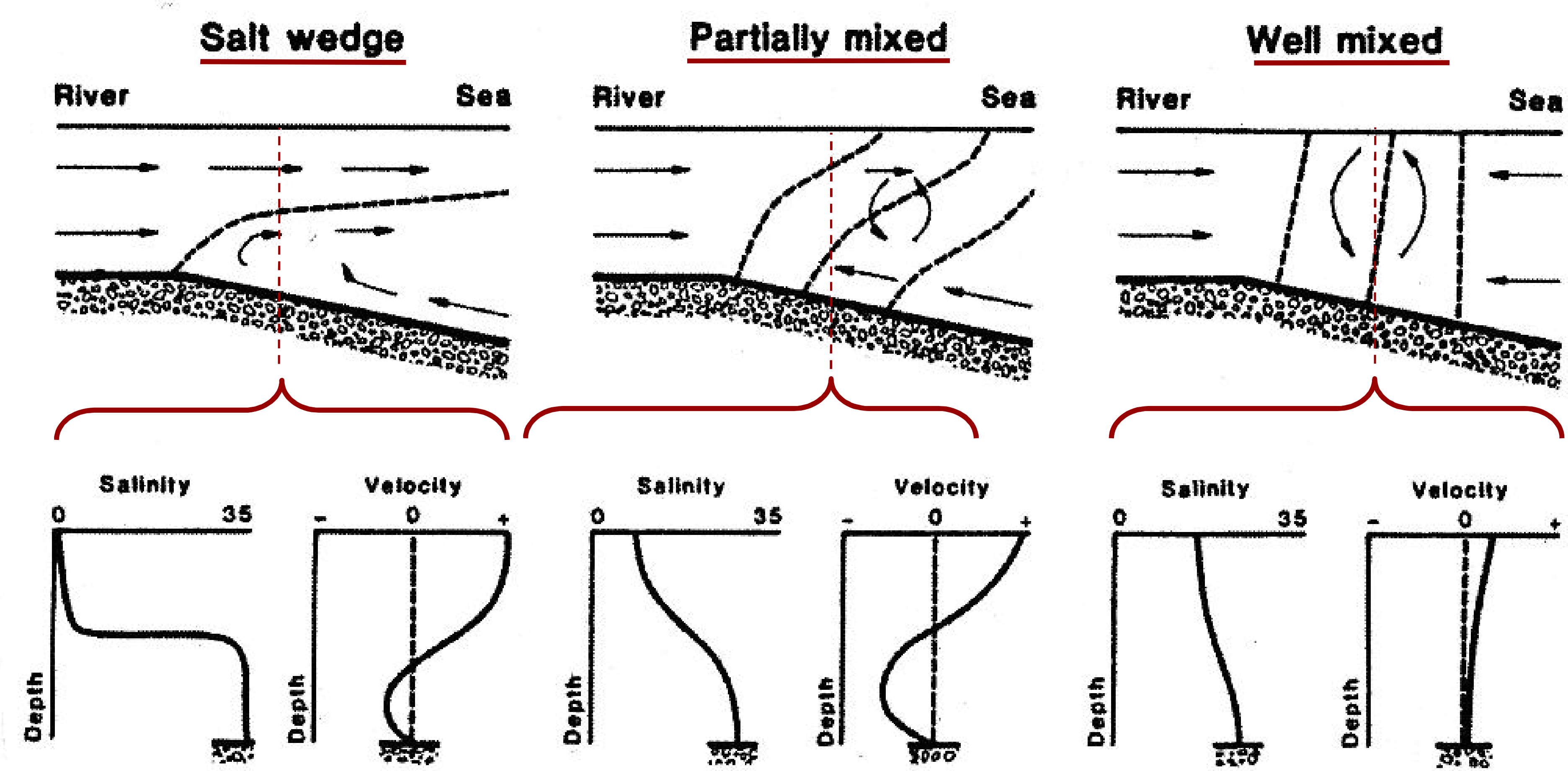


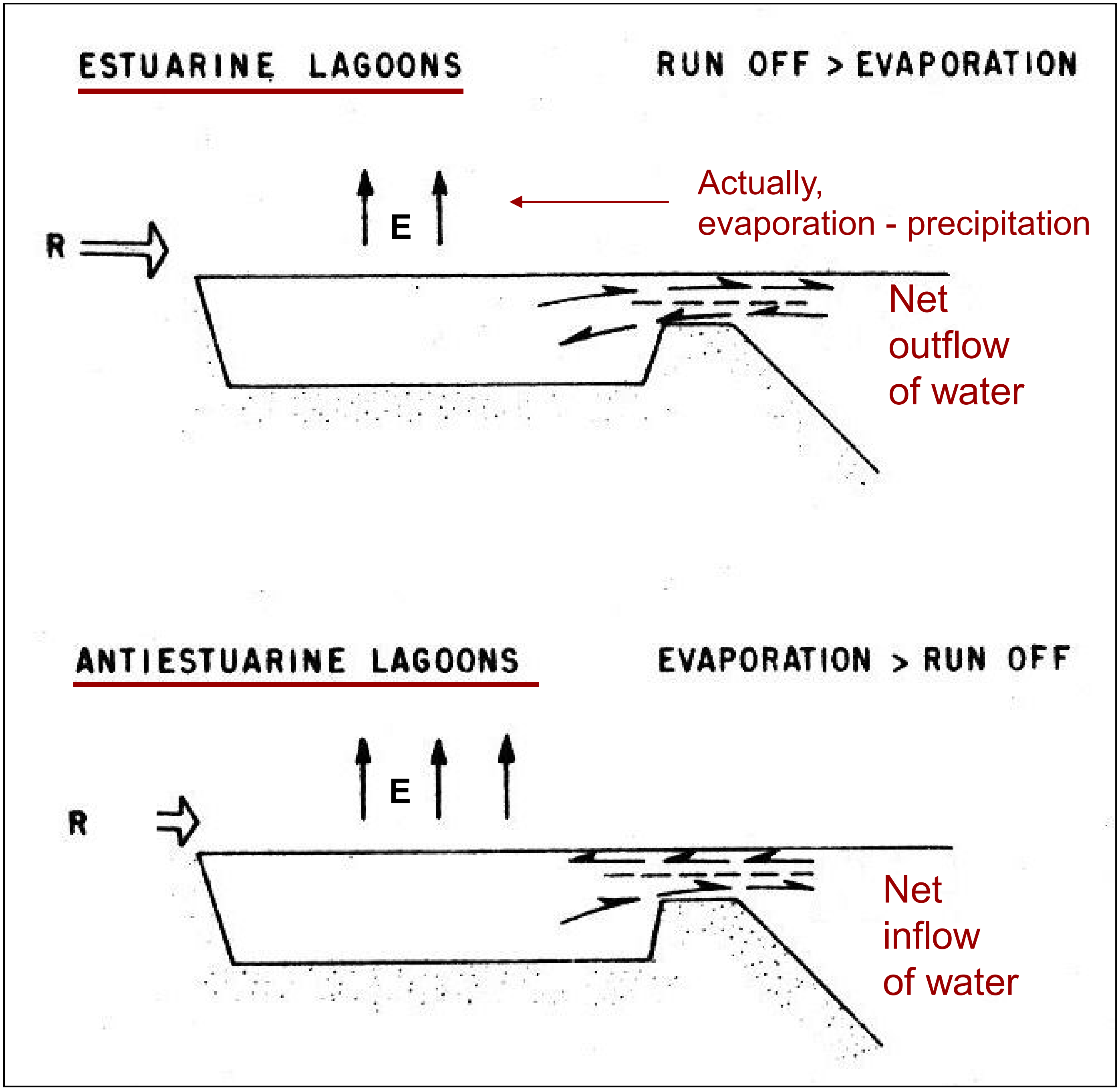

**Fig. 112.** Idealized map of a typical estuary showing three divisions, lower, middle and upper estuary; the boundaries are transition zones that shift according to season, weather and tides (After Fairbridge, 1980)

Salomens and Forstner (1984)

**Fig. 1.2. Estuarine circulation patterns, isohaline structure and typical vertical profiles of salinity and residual velocity in mid-estuary.**




What factors determine the type of estuary??


ESTUARINE LAGOONS
RUN OFF > EVAPORATION
Actually,
evaporation - precipitation
R
E
Net
outflow
of water
ANTIESTUARINE LAGOONS
EVAPORATION > RUN OFF
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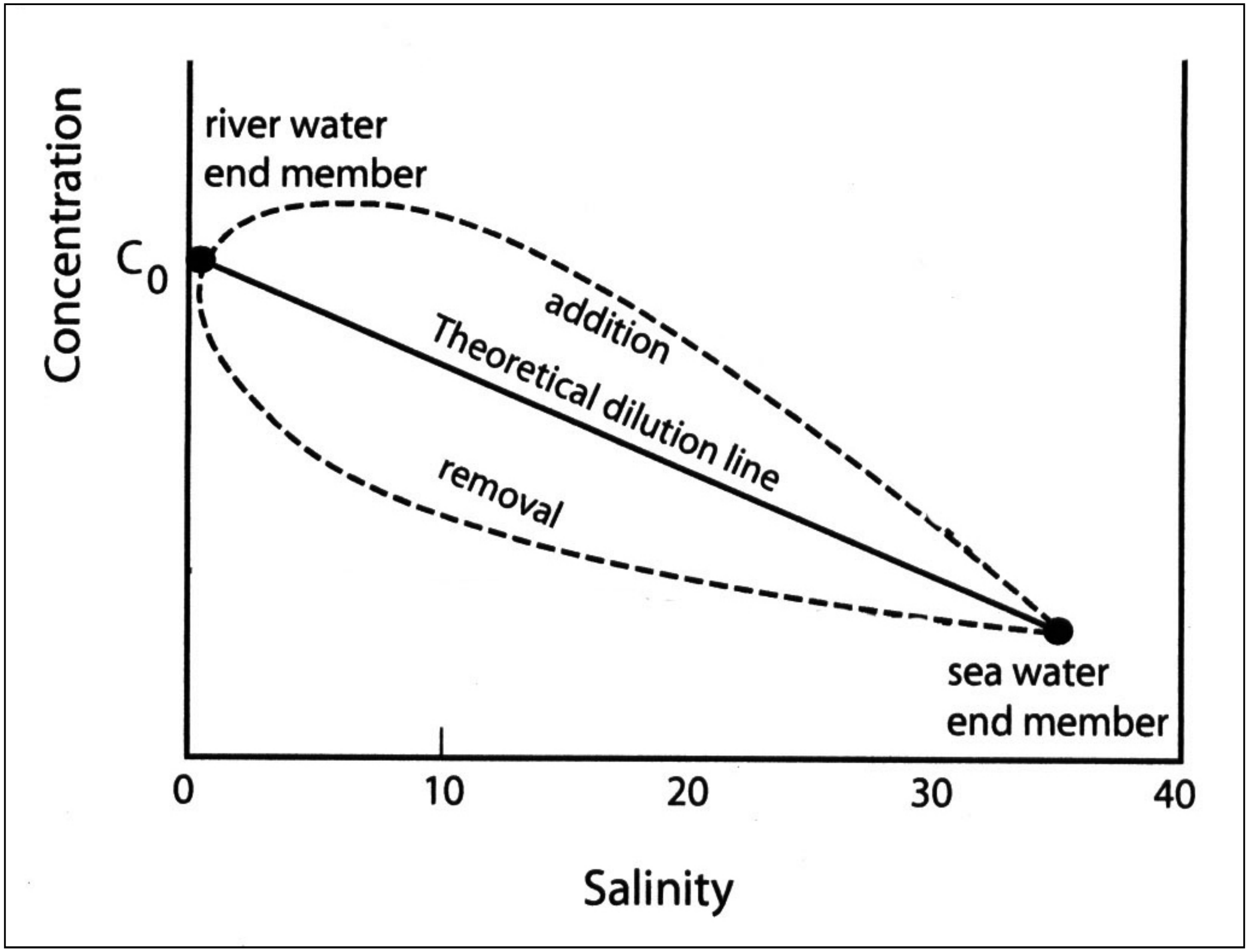
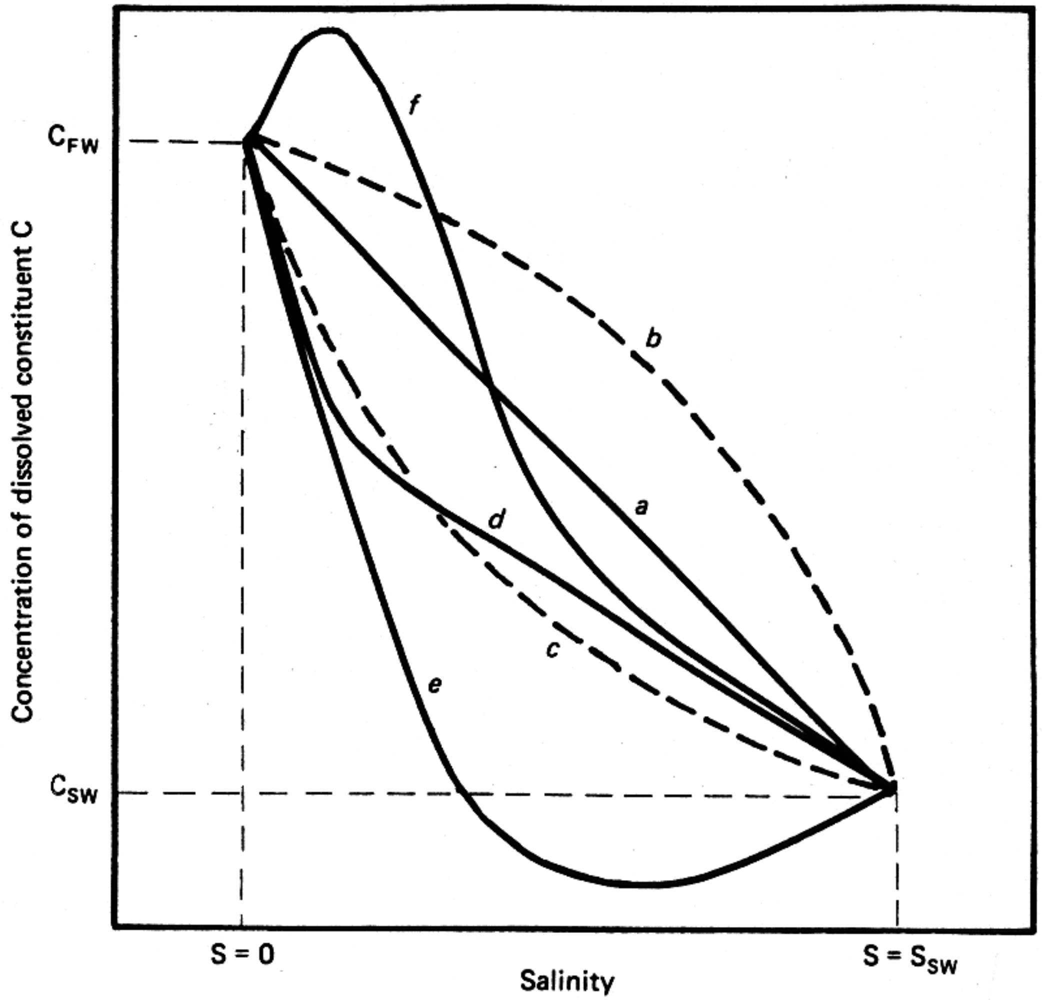
# Mixing Curves

## The Basic Tool for Studying River-Ocean Interactions




Assumes end-members are constant over the flushing time of the estuary

Fig. 1.6. Model dissolved constituent–salinity relationships in an estuary under steady-state conditions. $C_{FW}$ and $C_{SW}$ are the concentrations of constituent C in the fresh-water and sea-water mixing component, respectively. Line *a* defines the theoretical dilution line for a non-interactive constituent. Curves *b* and *c* indicate relatively widespread estuarine input and removal of C, respectively. Curve *d* is typical of removal occurring only in the upper estuary. Curve *e* is generated when the rate of removal of C in mid-estuary exceeds the riverine input. Curve *f* indicates net input of C to the upper estuary coupled with net removal further seaward.



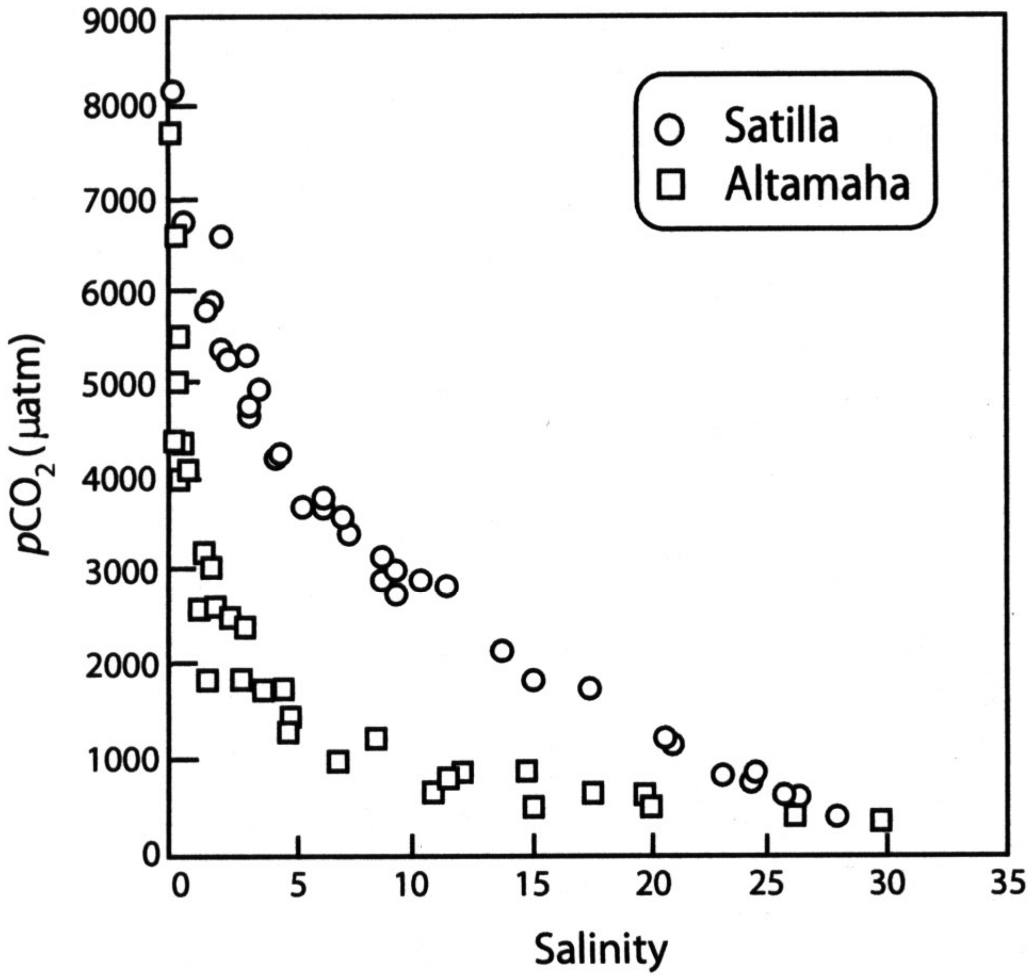



Figure 5.3 Calculated values of partial pressure of $CO_2$ ($pCO_2$), based on dissolved inorganic carbon (DIC) and pH data, versus salinity in estuarine waters of the Satilla and Altamaha Rivers (USA). (Modified from Cai and Wang, 1998.)

# Variation in End-members Over Time-scales Shorter Than the Time-scale of Estuarine Flushing

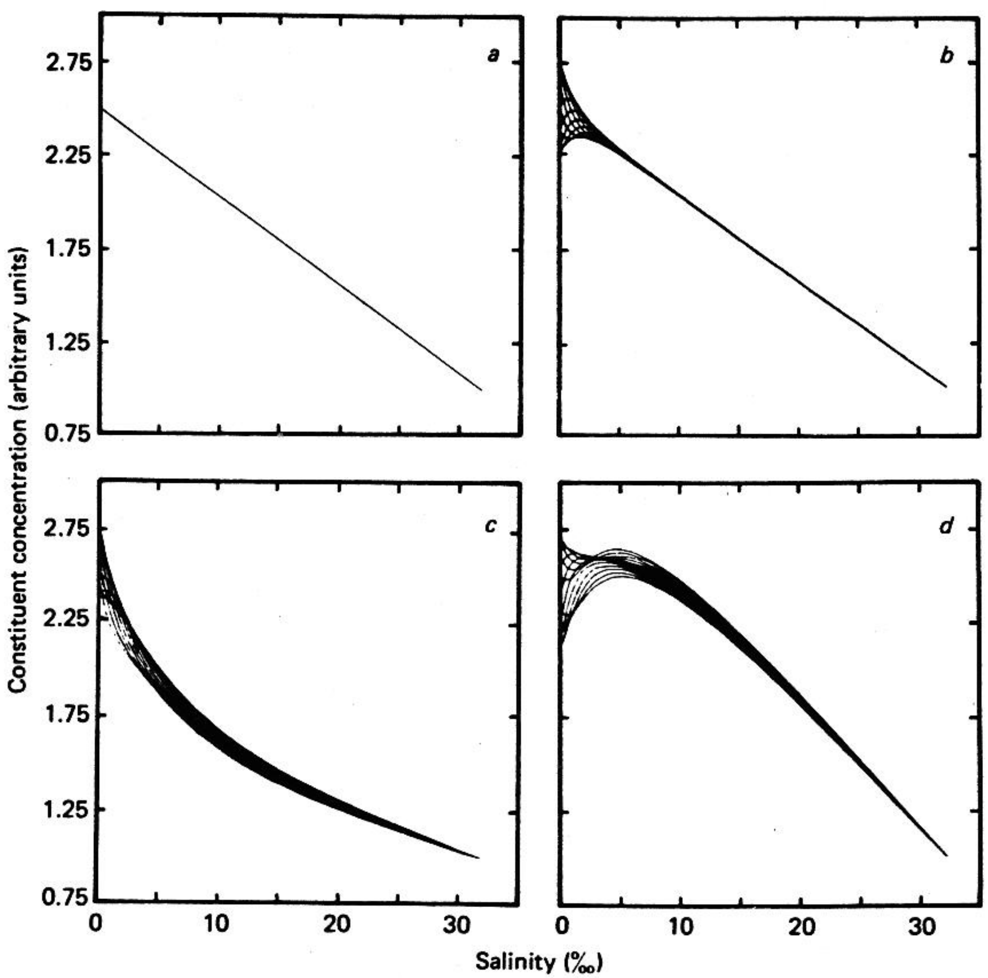



**Fig. 1.7.** Model constituent-salinity relationships in an estuary of flushing time *T*, for a non-interactive constituent subject to variations in fresh-water input concentration. In each case, the saline end-member (salinity 32 ‰) is maintained at unit concentration and the time-averaged concentration in the fresh water is 2.5 units. *a* shows the theoretical dilution line for invariant fresh-water concentration. The family of curves in *b* defines the envelope covering the constituent–salinity relationships generated when the fresh-water concentration oscillates sinusoidally with an amplitude of 0.5 units and a period of *T*/10. the curves in *c* and *d* are generated when an additional long-term oscillation of amplitude 1.5 units and period 5 *T* is imposed. These cover the changes in constituent–salinity relationships through a period *T*, during increasing and decreasing phases, respectively, of the longer-term oscillation. Reproduced from Loder & Reichard (1981) with permission of the Estuarine Research Federation.

Head (1985)

Apparent estuarine additions or losses may instead be due to temporal variability in the endmembers!

# An Example of Seasonal Effects

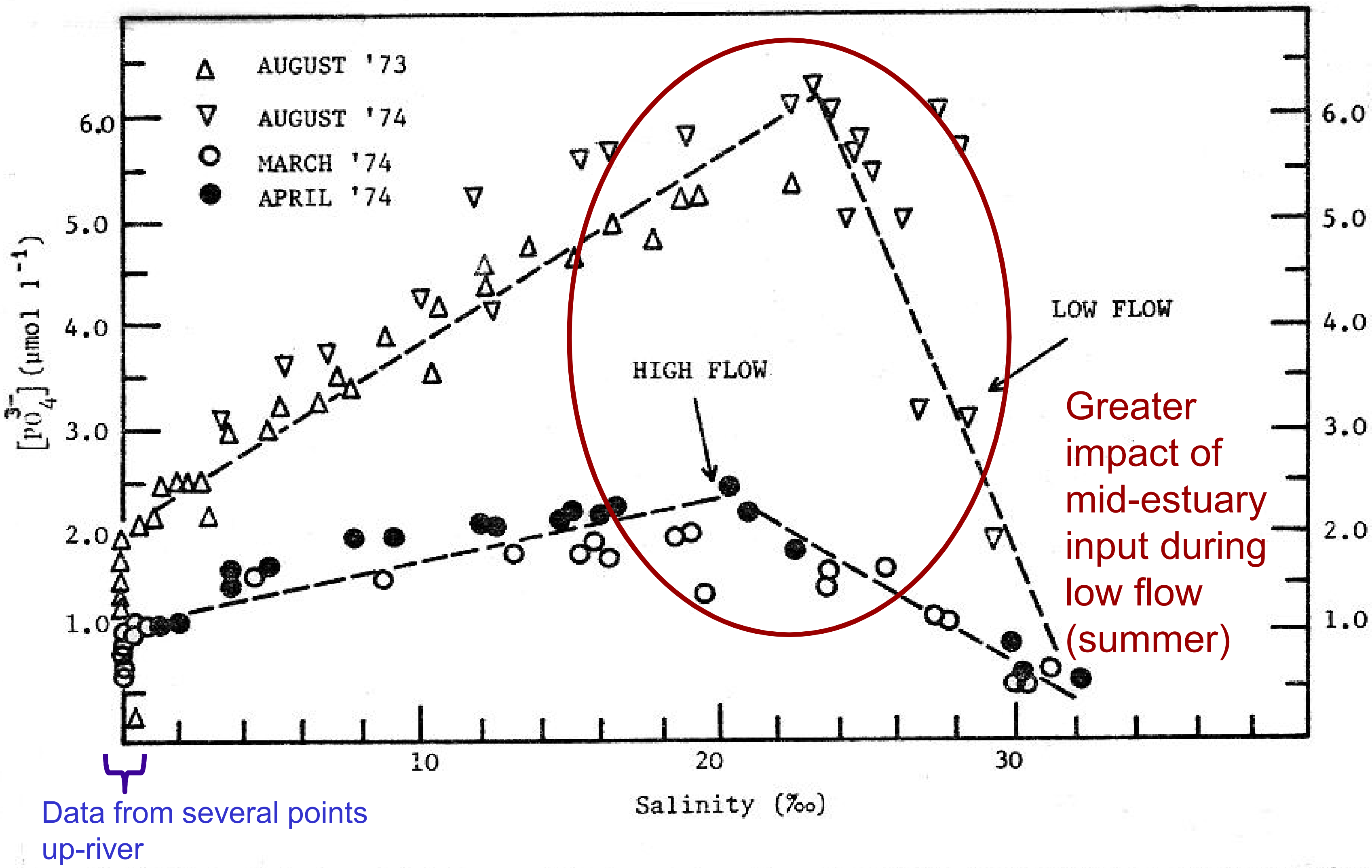



FIG. 41.8. Phosphate (molybdate-reactive) as a function of salinity in the Hudson Estuary (after Simpson *et al.*, 1975). Results for high-flow and low-flow conditions are illustrated.

Table 1.3. *Factors which impose temporal variability on the composition of water at a fixed geographical position in an estuary*

| Form of variability | Frequency | Process |
|---|---|---|
| *Cyclic fluctuations about average conditions* | | |
| 1. Small scale random fluctuations about mean level or trend | < Seconds to minutes | Turbulent eddy structure of water in mixing regime |
| 2. Variability around mean level or trend | Minutes to hours | Eddying; incompletely mixed inputs; temporary isolation of water, e.g. in bays or over mud flats |
| 3. Regular interruptions to mean level or trend | Often tidal | Intermittent discharge |
| 4. Regularly cyclic | Usually 12½ hours, with spring/neap variations in amplitude | Tidal advection |
| 5. Regularly cyclic | Annual | Biological and/or climatic cycles |
| *Intermittent fluctuations* | | |
| 1. Irregular interruptions to mean level or trend | — | Irregular discharge |
| 2. Intermittent significant change in water characteristics | Often annual, i.e. more probable at certain times of year | Climatic effects, e.g. exceptionally high or low fresh water run-off; storm surges; biological instability (plankton blooms) |
| 3. Permanent discontinuity in water characteristics | — | Change in exploitation, e.g. new discharge. Natural phenomenon, e.g. morphological adjustment to estuarine bed form, rechannelling |
| *Trend* | | |
| 1. Persistent year to year trend | — | Change in exploitation, e.g. continuous increase or decrease in discharge. Natural estuarine evolution, e.g. continuing siltation |

# The Mid-estuary Turbidity Maximum

Expected:

Turbidity max is due to both 1) chemical flocculation and 2) sediment resuspension

Measured:

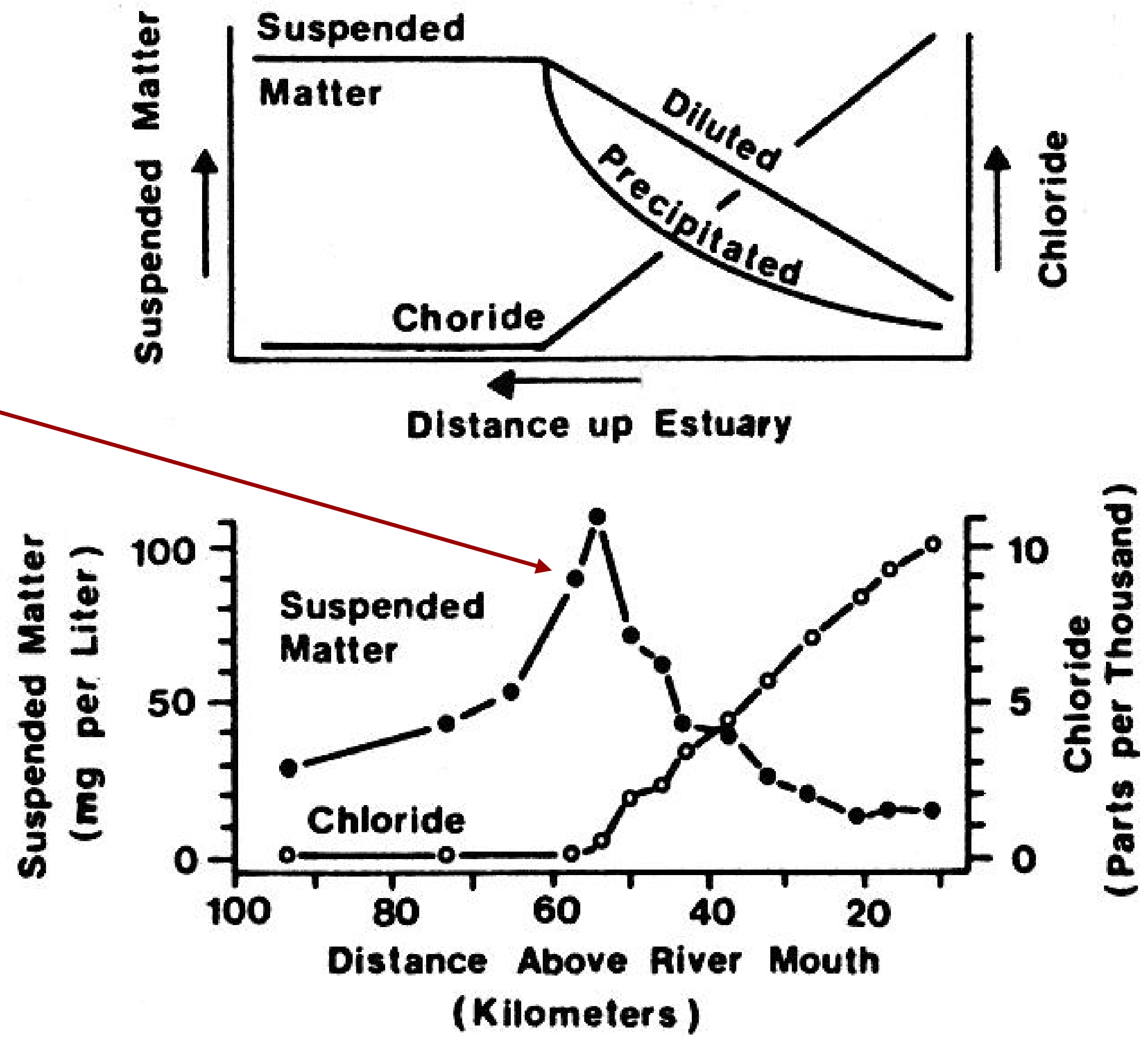
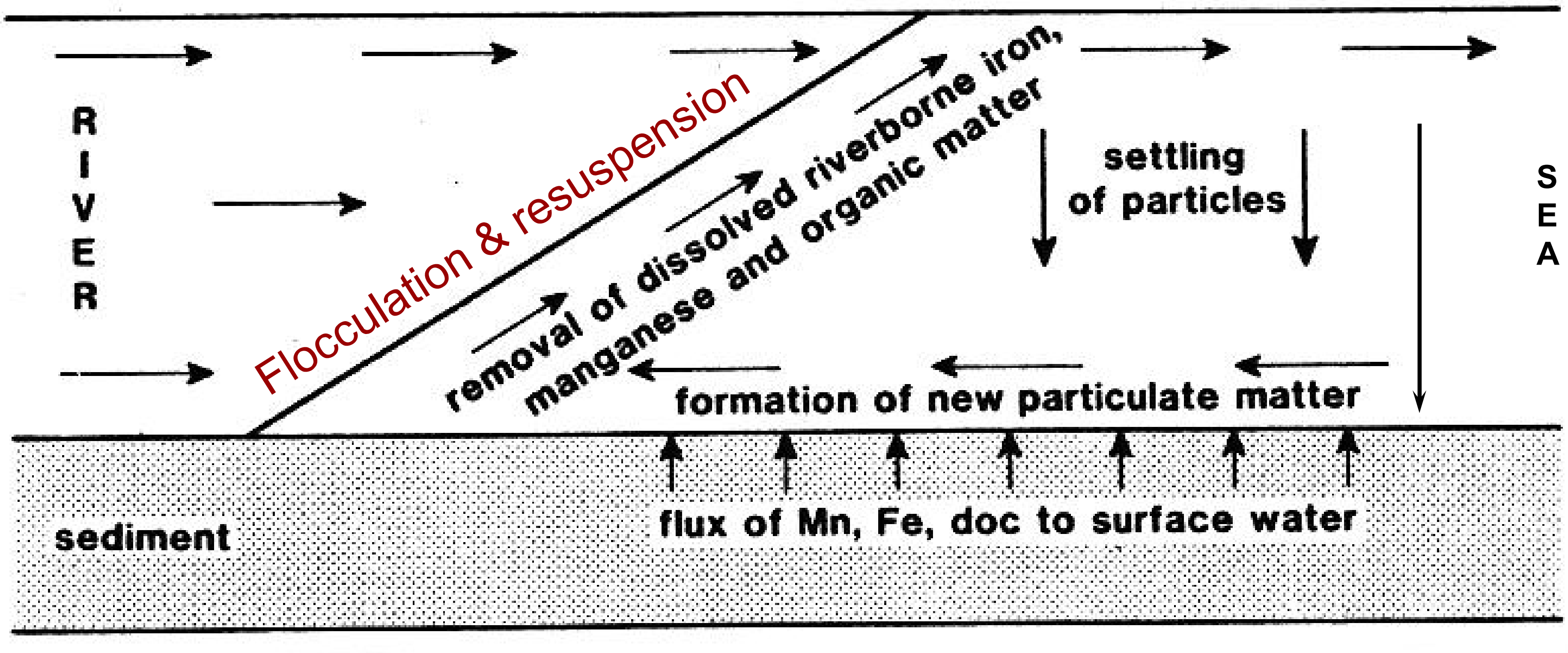
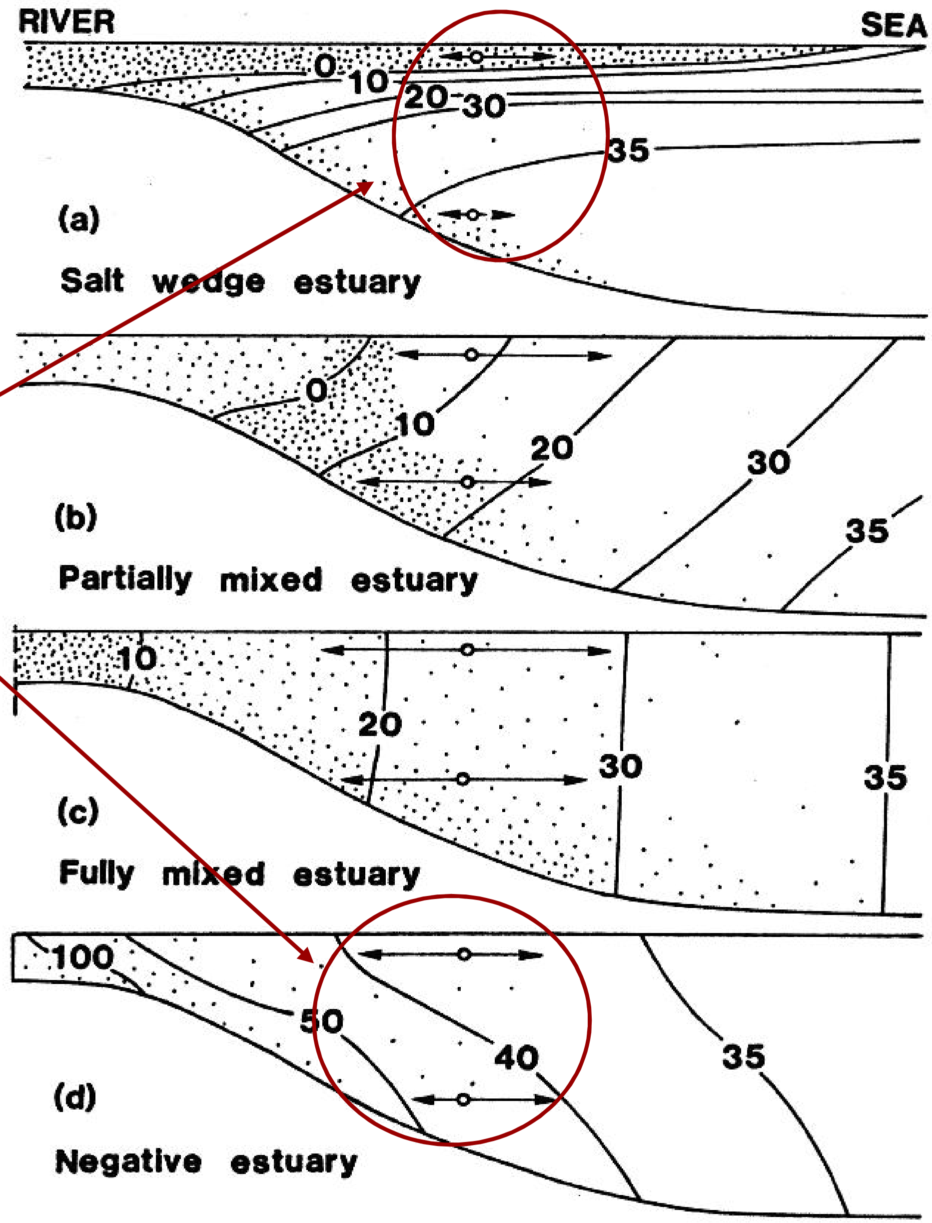



**Fig. 115.** Example of the non-conservative behaviour of suspended matter in estuaries and the formation of a turbidity maximum at the fresh-sea water interface (Meade, 1972)

# A Mid-estuary Trap for Riverborne Material



# Particle Distribution *vs.* Estuary Type




Note tidal asymmetries

**Fig. 113.** Schematic presentation of types of estuaries. The dots indicate sediment concentration and the arrows the net water movements over ebb and flood. (Postma, 1980). 0–35 are ‰ Salinity (S) isolines. For explanation see the text

# Effects Of The Mid-estuary Particle Maximum

1. Scavenging of surface-active materials
   - 70-100% of riverine Fe is removed (most at low salinity)
   - 60-80% of humic acids is removed
   - 5% of total DOM is removed

2. Increased turbidity
   - Lower primary production
   - Reduction of photochemical reaction rates

3. Enhanced transport rates downstream / offshore
   - Enhanced sedimentation rates downstream / offshore

# An Estuarine Summary

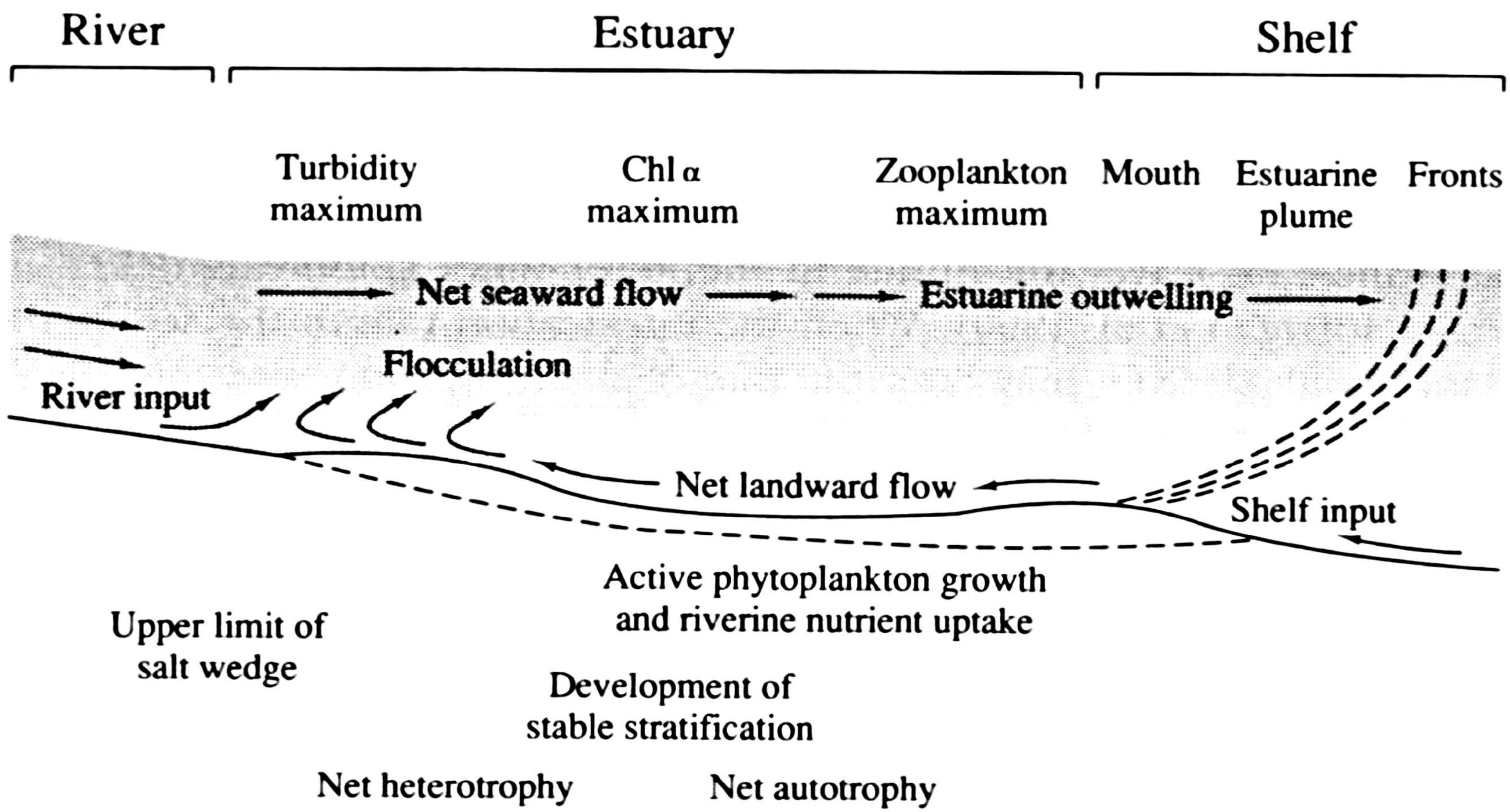
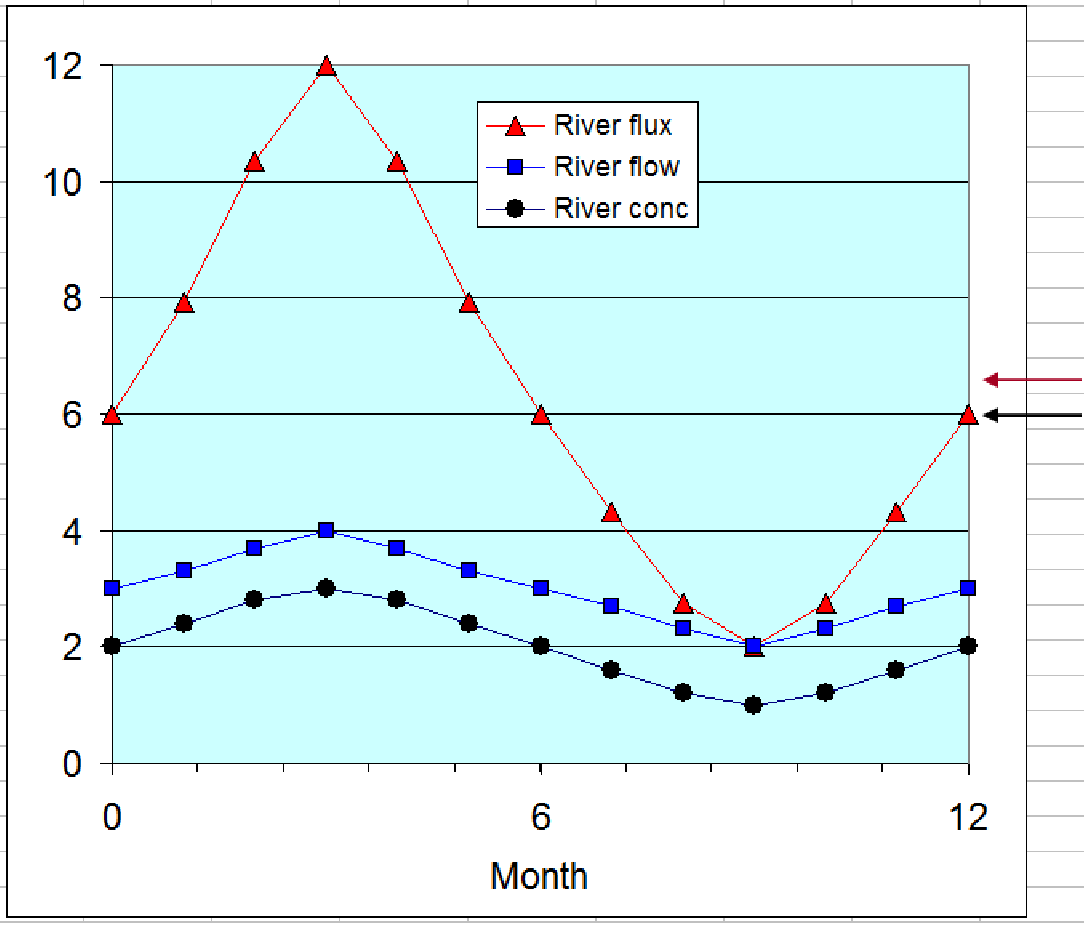



**Figure 8.13** Conceptual model of the chemical and biological structure in estuaries. As the suspended load settles from the entering river waters and nutrients are made available, phytoplankton production increases, fueling an increase in zooplankton production and higher trophic levels. From Fisher et al. (1988).

# Computation of Annual Mean River Flux

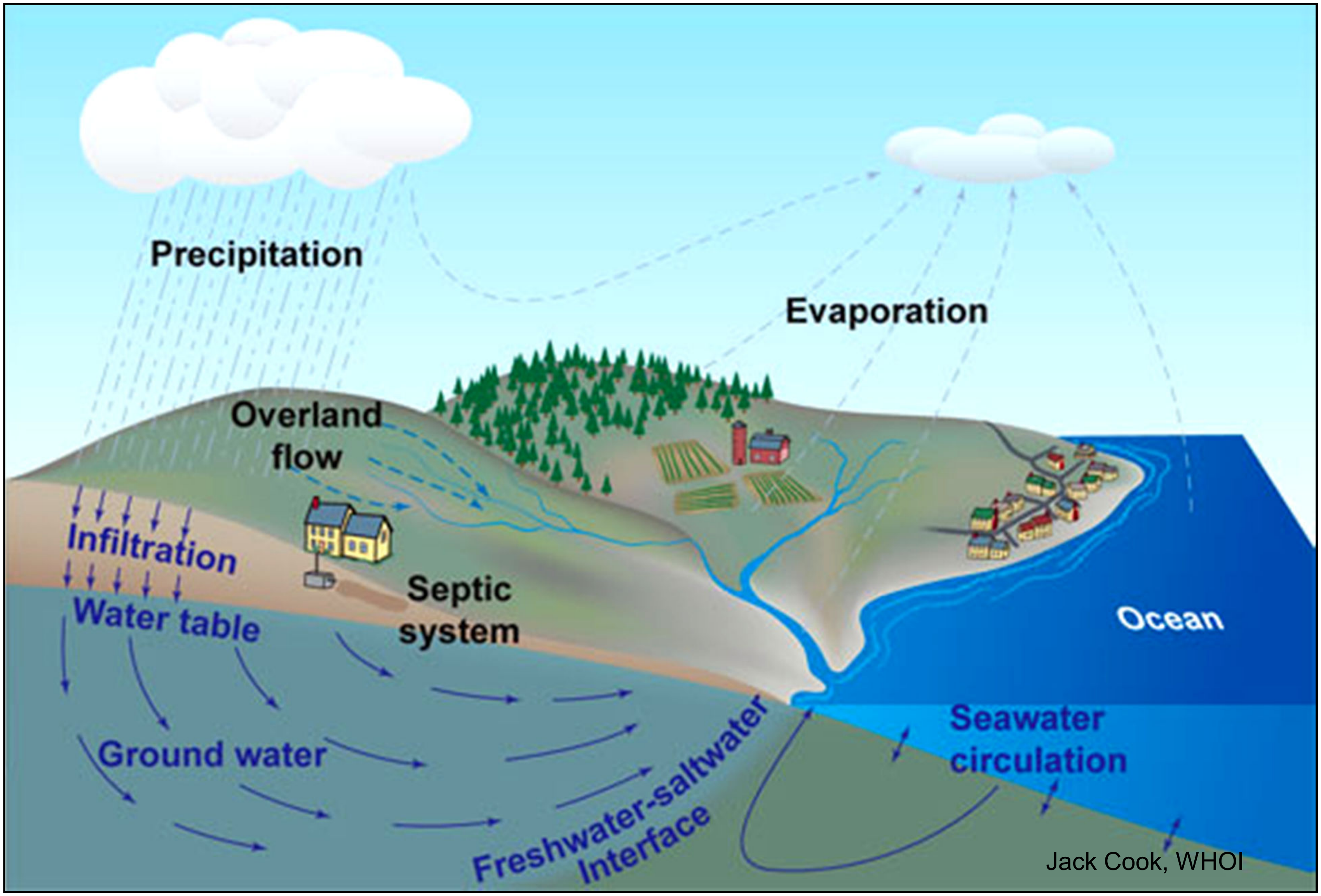
**Means of products vs. products of means**

| *Month* | *Conc* | *Flow* | *Conc x flow* |
|---|---|---|---|
| 0 | 2 | 3 | 6 |
| 1 | 2.4 | 3.3 | 7.92 |
| 2 | 2.8 | 3.7 | 10.36 |
| 3 | 3 | 4 | 12 |
| 4 | 2.8 | 3.7 | 10.36 |
| 5 | 2.4 | 3.3 | 7.92 |
| 6 | 2 | 3 | 6 |
| 7 | 1.6 | 2.7 | 4.32 |
| 8 | 1.2 | 2.3 | 2.76 |
| 9 | 1 | 2 | 2 |
| 10 | 1.2 | 2.3 | 2.76 |
| 11 | 1.6 | 2.7 | 4.32 |
| 12 | 2 | 3 | 6 |
| | | | |
| **Mean:** | **2** | **3** | **6.39** |



# Submarine Groundwater Discharge

## "The Subterranean Estuary" at the Land-Sea Margin



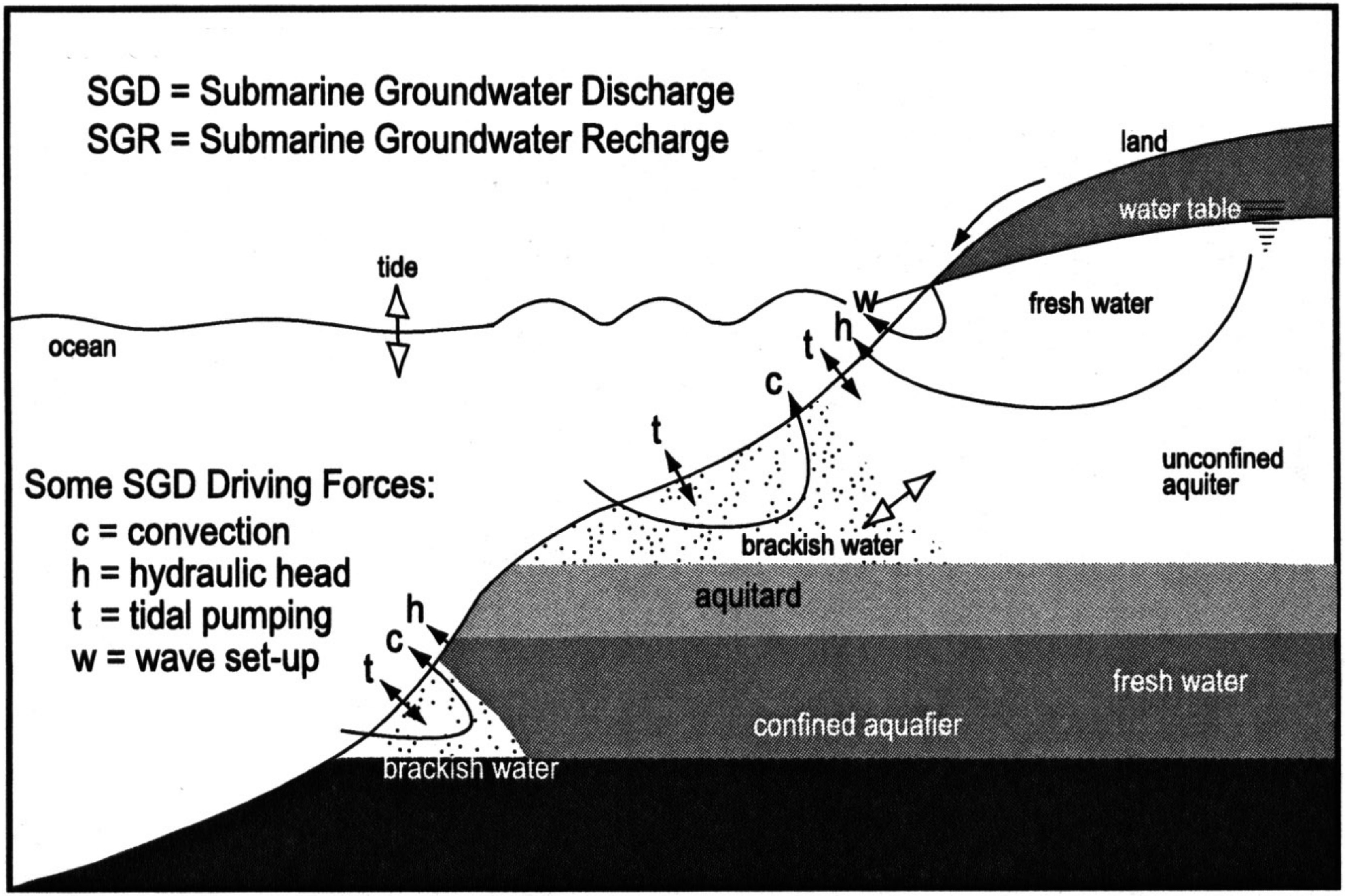
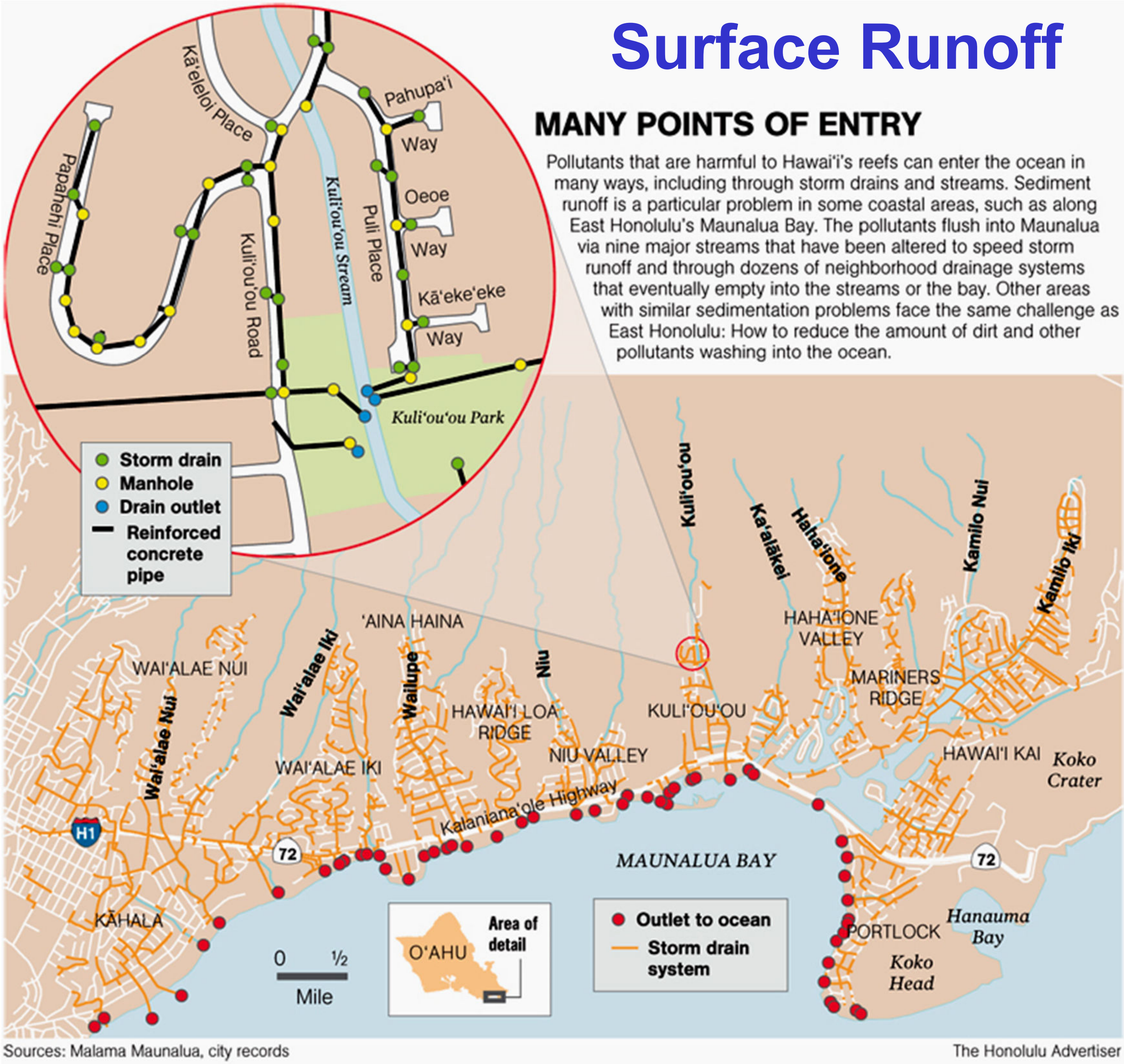



**Figure 16.5** Illustration of fluid transport processes associated with submarine groundwater discharge and recharge. Arrows denote fluid movement (Modified from Burnett et al., 2003).

# Surface Runoff



# Next class: Estuarine and Coastal Biogeochemistry

- Salinity changes are accompanied by chemical changes (nutrients, pH, $O_2$, redox, etc.)
- Sediment trapping (and subsequent organic matter oxidation) occurs because of slowed flow
- Nutrient and organic loads to estuaries are typically high and are often influenced by pollution sources
- Primary production is typically elevated, but estuaries may be either net autotrophic or heterotrophic