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Estuarine hydrology

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Introduction

The word estuary is of 16th century origin and originated from the Latin *aestuarium*, which means marsh or channel, and this is derived from the Latin *aestus*, meaning tide or billowing movement. Estuaries are transitioning environments between the land and the ocean, where fresh water coming from the rivers mixes with saline oceanic water. This river inflow needs not be perennial. There are several definitions of estuaries. For freshwater scientists the main thing is to define the head of an estuary; in one definition this is the salinity limit; in another definition this is the tidal limit; and in still another definition it is the source of the fluvial sediment. For coastal scientists and oceanographers, the mouth of an estuary, i.e. the point where an estuary ends, is also ill-defined. It can be a geographic feature or the seaward edge of a tidal plume in the open ocean.

Whatever the geographical definition, an estuary is a zone of transition with gradients in salinity, sediment characteristics, turbidity of the water column, chemical composition including nutrients, dissolved gases and trace metals and in diversity and productivity of species of animals and plants. Estuarine waters are commonly more biologically productive than the oceanic waters. In addition, estuaries are strategic locations for human development; nearly 69 % of the largest cities in the world are located on river estuaries. The scientific understanding of estuaries is thus of great practical importance.

An estuary is never at a steady state. Its bathymetry is continuously evolving. Forced by tides, waves and river inflows, estuarine water is continuously moving and with it its ecology is also continuously evolving. Some largest estuaries may have the additional direct influence of winds on the local circulation such as the Amazon River. The resulting physical and biological features of an estuary and its ecosystem health are determined by the time scales of the processes controlling the movements of water and sediments and the ecological processes in the water and on the bottom.

Genesis and geomorphologic time scales

The physical features of an estuary are determined firstly in a time scale of centuries from the recovery of the global mean sea level (MSL) from the last glaciation (i.e. eustatic variation) and the tectonic movements that resulted (i.e. isostatic variation), and secondly in a shorter time scale from human-induced changes in river discharge Q_f and riverine sediment inflow Q_s . Global MSL was 120-130 m lower 20,000 years ago than at present (Fig. 1a). The melting of the ice resulted in a rebound of the continental plates relieved of the pressure of ice glaciers. As a result the relative MSL varied spatially in three zones (Figure 1b) of, respectively, on-going decrease, relative stability, and on-going small increase (Figure 1c). The global MSL has been fairly constant the last 6,000 years. It is now at a high stand level that was last reached about 120,000 years ago. Old river and flood plains became flooded by rising seas; estuaries were formed as they filled with sediment originating from the watershed and from the sea; watershed sediment were brought in by rivers and coastal sediment were brought in by tides and storms.

(a)

(b)

(c)

Figure 1. (a) Time series plot of the global mean seal level over the last 140,000 years. (b) The approximate distribution of the coasts that followed one of the three typical relative mean sea-level curve types A, B and C as shown in (c). Redrawn from Wolanski et al. (2009).

Thus most estuaries have not reached a steady state yet; they are still evolving. They have an age; they all started young, many have reached maturity though not the fjords, and some have reached old age meaning that they cannot accommodate any additional sediment. The extra sediment is carried seaward to be dispersed at sea or to form a delta. An old estuary can be rejuvenated when a major river flood creates a new river mouth.

As sketched in Figure 2, the infilling of an estuary of volume V is controlled by the inflow of riverine sediment Q_s , the net balance ΔQ_s between seaward ocean

flux $Q_{s,out}$ and the landward sediment flux from coastal water $Q_{s,in}$, and the sediment flux to lateral storage in the flood plains $Q_{s,storage}$. The geomorphologic age of an estuary is the time it takes for the net sediment flux to fill the volume V . The aging of an estuary can be greatly accelerated by human activities in the watershed, mainly land-clearing. As an example this geomorphologic age T was estimated for a number of macro-tidal, muddy estuaries in the Pacific region (Figure 3); T varies between several thousand years for estuaries that are non-impacted by human activities (rank 1), to several hundreds of years for estuaries that are moderately impacted by land clearing in the watersheds (rank 2), to only several tens of years for estuaries that are severely impacted by land clearing in the watersheds (rank 3), illustrating the rapid acceleration of the aging of estuaries by siltation due to land-clearing in the watersheds.

Dams on the other hand can trap sediment in reservoirs and thus prevent sediment to reach the estuary, which slows down the estuarine aging process. This is particularly the case for micro-tidal and tideless estuaries. Before the mega-dam was constructed some riverine sediment was trapped in the estuary that usually comprised a lagoon and a delta; the rest was exported to the sea (Figure 4a). The mega-dams in the Colorado and the Nile rivers have stopped all (most) river floods export of water and sediment to the sea (Figure 4b) and significantly decreased the inflow of sediment to the estuary. The channels are silting slower, i.e. aging slower, than before due to lesser sediment inflow from the dam, while the coast is eroding.

However in macro-tidal estuaries, large dams can accelerate the aging of estuaries. This is because they can decrease or even stop large river floods; this prevents seaward flushing of estuarine sediment and accelerates tidal pumping of coastal sediment landward into the estuary; these results in siltation and thus aging the estuary. At the same time however the coast becomes starved of sediments, which are exported by waves and currents in the open sea; as a result the coast erodes.

Figure 2. A sketch of the net sediment budget in an estuary.

Figure 3. The geomorphologic age of macro-tidal, muddy estuaries in the Pacific.

Figure 4. A sketch of the sediment budget in the micro-tidal Nile and Colorado deltas (left) before and (right) after dam construction.

Sediment dynamics time scales

Estuarine sediments are of two types: cohesive sediment (also called mud or clay) have a mean particle size $d_{50} < 4 \mu\text{m}$; non-cohesive sediment (sand) has a $d_{50} > 64 \mu\text{m}$. Silt has a d_{50} in between those of mud and sand; it is weakly cohesive.

The sediment dynamics depend on the currents, the salinity, the type of sediment and the biology. Sand is mainly carried along the bottom and very close to the bottom. Mud is mainly carried in suspension within the water column.

There are several models, pioneered by engineers, to calculate the sand transport as bed load. The models generally assume either that the sand moves as a creeping movement of layers along the bottom or that the sand particles are rolled and tossed over the bottom in a process called saltation. The models are based on laboratory studies and estimate the bed load transport as a function of the mean particle size d_{50} , the current-induced stress, a threshold stress for bed load to commence, and the difference in density between the water and the sediment. They yield at best order-of-magnitude estimates and thus must be used with caution. Sand is often mixed with mud and even if the sand is the dominant fraction the clay particles modify the bed load by a factor of 2 to 4.

Cohesive sediment (mud) behaves differently than non-cohesive sediment (sand) because it forms flocs typically 100-200 micron in size. Flocculation is initiated by salinity ions that cause electrostatic forces between the small sediment particles and greatly enhanced by the bacteria and plankton that, through the production of transparent exopolymer particles (i.e. a mucus) aggregate flocs to form

extremely large flocs (commonly 1000 micron in size) and called marine snow flocs. In very turbid waters the suspended sediment concentration SSC ($\text{SSC} > 500 \text{ mg l}^{-1}$), marine snow is scarce; in less turbid waters (typically $\text{SSC} < 100 \text{ mg/L}$), marine snow is common. The biology also controls the erodibility of the bottom sediment because algae mats stabilise the bottom sediment and animal burrows may loosen the sediment and facilitate erosion. There are models, pioneered by engineers, to calculate the mud transport as a suspended load. They are largely based on laboratory experiments and they generally fail in the field because the laboratory experiments cannot account for the biology in the field.

The vertical profile of SSC takes many shapes, from vertically nearly well-mixed (line a in Figure 5), to smoothly increasing with depth (line b), to a step structure called the lutocline for $\text{SSC} > 5 \text{ kg m}^{-3}$ (line c). Because the suspended sediment increases the density of the water, the water density changes across the lutocline. This reduces the vertical diffusion coefficient K_z in the lutocline, in the same manner that a thermocline inhibits vertical mixing between the hypolimnion and the epilimnion. This helps preserve a fluid mud layer near the bottom.

Figure 5. Three typical vertical profiles of suspended sediment concentration in estuaries.

Riverine mud in suspension commonly reaches the estuary unflocculated. On reaching the estuary this mud flocculates as a result of the action of salinity and the biology (Figure 6a). Salinity-driven currents, tidal currents and weaker cohesive forces of silt flocs as opposed to mud flocs generate a physical filter that sorts the silt

from the clay (Figure 5a) and that creates a turbidity maximum zone (Figure 5b). Marine muddy snow forms a biological filter that inhibits the export of mud from estuaries (Figure 6c). Finally the riverine mud mixes with, and is diluted by, the estuarine mud through erosion and sedimentation as a result of floods, waves, tides and storms (Figure 6d). In some estuaries the tidal currents are larger during the rising tide than during the falling tide; in those estuaries the tides pump the sediment landward. These processes greatly increase the residence time in the estuary of the riverine mud and its particulate pollutants and nutrients.

Figure 6. (a) The physical filter of fine sediment that generates (b) a turbidity maximum zone, i.e. a zone with the highest suspended sediment concentration (SSC); the SSC curve varies with the tides. (c) Biologically-produced transparent exopolymer particles and fine sediment in suspension interact to produce muddy marine snow flocs that accelerate the settling of the mud and generate a biological filter inhibiting the export of fine sediment seaward. (d) Riverine mud is diluted by estuarine mud.

If the estuary is sandy, the sediment is also trapped in the estuary and the trap is also leaky, with sediment imported both from the sea and from the rivers and exported offshore during large river floods. The evolution of a sandy estuary geomorphology is difficult to predict because of the difficulties in measuring sandy sediment fluxes. Observations suggest that the dominant forcing functions controlling the movement and trapping on sandy sediments in estuaries are the oceanography (tidal dynamics and storms) and the hydrology (floods).

Classification based on geomorphology and on water circulation

Estuaries may be classified upon their geomorphology or physical oceanography.

The estuarine types based on the geomorphology, are mainly 1) drowned river valleys, (2) lagoon-type or bar-built, (3) fjords. Most of the drowned river valleys were formed with the sea level rise on low and wide coastal plains (e.g. Chesapeake Bay, Tampa Bay and Delaware Bay). The lagoon types are semi-isolated from coastal waters by barrier beaches and some lagoons are extremely large (e.g. Lagoa dos Patos in Brazil that is 242 km long, and the Mirim Lagoon in the border between Brazil and Uruguay that is 290 km long, and the well-known Venice Lagoon, famous in human history). These estuaries have only a few narrow inlets allowing the interaction between the estuary and the coastal zone. The fjords were formed in deeply eroded valleys caused by the glaciers; many of them have shallow areas near the estuarine mouth, and thus restricting the water flow. Fjords often have lower temperatures than coastal waters (e.g. the deepest fjord is the Sognefjord in Norway with depths up to 1300 m, and the largest fjord is Scoresby Sund in Greenland that is 110 km long).

The classification based on the estuarine circulation is based on the vertical distribution of salinity in the estuary, and the types are (1) salt wedge, (2) partially mixed, (3) well-mixed, (4) fjord-type, and (5) salt plug (Figure 7). In salt wedge and fjord-type estuaries, the river inflow greatly exceeds tidal currents, freshwater moves

as a distinct surface layer, and a sharp salinity interface separates the fresh/brackish water on top from the saline water underneath. In partially mixed estuaries the tidal currents only slightly exceed river inflow, and thus cause more vertical mixing, which reduces vertical salinity gradients. Well-mixed estuaries are dominated by tidal mixing, thus the vertical salinity stratification is negligible. Salt plug estuaries occur in the dry climates, where evaporation greatly exceeds river inflow, resulting in higher salinity in the estuary than at the mouth.

Figure 7. Classification of estuaries based on the physical oceanography.

Biological implications of sediment transport

At high SSC (highly turbid), there is nearly complete darkness. Typically, for suspended sediment concentration (SSC) = 0.2 g l^{-1} , visibility < 30 cm; for SSC = 1 g l^{-1} , visibility < 1 cm. The plankton in these turbid waters can only photosynthesise for the short time that it is brought to the surface by turbulence. The benthos has no such opportunity; it stays in complete darkness as long as the water stays turbid. In addition even in the absence of suspended sediments, light is attenuated with depth depending on the plankton (shading effect) and on dissolved organic matter (DOM).

Mud also affects pollutants (such as PCBs and heavy metals) and nutrients (particularly Phosphorus, less so for Nitrogen) because these particles are readily absorbed on the mud due to the electric and colloidal forces on the clay particles. Thus pollutants can stay trapped hundreds of years on settled mud and are released when the mud is resuspended. Suspended mud is important in absorbing dissolved

nutrients and largely making it unavailable by the plankton. This is quantified by the partition coefficient K_d

$$K_d = \text{mass absorbed on particulates} / \text{Total mass} \quad (1)$$

and this was quantified by Middeleburg and Herman for estuaries in Europe; they found at suspended particulate matter (SPM) of 10 mg/L about 10% of the organic Carbon may be present in particulate form, and this was about 50% at SPM of 100 mg/L and 80% at SPM of 400 mg/L. Phosphorus is also readily absorbed on suspended mud and Nitrogen less so. Thus in muddy estuaries the classical stoichiometry ratios for dissolved inorganic nutrients C:N:P=106:16:1 may not hold, and this invalidates the use of aquatic ecosystem models based on stoichiometry.

In muddy estuaries most heavy metals and a number of pollutants such as PCBs and POPs are nearly totally sequestered on mud particles; they are thus extremely slowly flushed out of polluted, muddy estuaries, and are thus a legacy of pollution that may last many decades, and even centuries, after the pollution source was stopped. This is the case for instance of Boston Harbour in the USA and the Elbe Estuary in Germany.

The impact of riverine nutrients on an estuary is very different for a sandy (clear water) estuary where the nutrient is readily bioavailable and light penetration allows photosynthesis, than for a muddy (turbid) estuary where much of the nutrient, especially phosphorus, is absorbed on the mud and photosynthesis is inhibited by the lack of light.

Tidal wetlands

The vegetation in tidal wetlands plays an important role in controlling the net sediment flux in or out of an estuary. These wetlands were originally non-vegetated intra-tidal mudflats are exposed at low tide and inundated at high tide. These mudflats commonly have a tidal creek that focuses the largest currents in the creek; the currents remain small in the surrounding flats where sediment can thus accumulate. These non-vegetated mudflats are often unstable and are readily modified by storms. All this changes drastically when the sediment accumulation results in the substrate rising above mean sea level. At that stage the vegetation establishes itself, consisting typically of salt marsh plants in temperate climate and mangroves in tropical climates.

Through its roots below ground the vegetation helps stabilise the tidal creek; through its structure above ground the vegetation accelerates sedimentation by slowing down the water and thus enabling the suspended sediment entering the intertidal areas at rising tide to deposit. The difference between the sediment that comes in at rising tide and the sediment that goes out at falling tide is the sediment trapped in the tidal wetlands. This role of vegetation is crucial in enhancing sediment trapping in estuaries; for instance a mangrove that covers 3.8% of the river drainage area traps 40% of the riverine mud inflow; a salt marsh where plant height exceeds 8 cm may enable sedimentation at a rate of up to 8.2 cm yr^{-1} ; the rate of sedimentation of British saltmarshes averages 4.3 mm yr^{-1} and a similar result is also found in U.S. saltmarshes. Storms may disturb this trend in the short-term.

Tidal wetlands comprise globally mainly mangroves and saltmarshes. Mangroves worldwide cover an area of about $240,000 \text{ km}^2$ and are the dominant coastal wetland in subtropical and tropical regions where frosts do not occur. Saltmarshes are distributed worldwide, mainly in areas subject to frosts where mangroves do not grow and in the higher grounds next to mangroves; thus they are most common in middle and high latitudes; their vegetation comprises mainly salt-tolerant grasses and rushes. Mangroves and saltmarshes vegetation exhibit zonation patterns whereby the vegetation is the thinnest in the areas of lowest elevation where sediment accretion occurs. A mild slope in the vegetated wetlands forms a drainage pattern toward the tidal creek.

The importance of tidal wetlands to the estuarine ecosystem is not limited to sequestering nutrients and pollutants. Tidal wetland vegetation converts excess nutrients in the flowing waters into plant biomass; in turn this plant biomass supports an ecosystem. Organic detritus such as plant litter is exported from the wetlands to the estuary. The wetlands also provide a nursery for fish and crustaceans that come in from the estuary – and the sea for migrating species - to feed and shelter within the saltmarsh and later return to the estuary or the sea; this forms an important exchange of organic nutrients between the tidal wetlands on the one hand and estuarine and coastal waters on the other hand. The nutrient outwelled from tidal wetlands increases the estuarine plankton community, which in turn support commercial fisheries of fish and shrimps, the success of which is closely linked to tidal wetlands.

The water transport time scales

The movement of water in an estuary is controlled by the tides, the river inflow, rainfall and evaporation, the wind, and events at sea such as storms. The multitude and variety of these factors, their interaction with the often shallow and highly irregular bathymetry, contribute to a complex non-linear and unsteady three-dimensional hydrodynamics.

Models of varying complexity can be used order to describe and quantify the transport of pollutants and the renewal of water.

Box models, in particular, are often used for a quick assessment of the flushing capability of an estuary. In the simplest approach, the estuary is modeled as a single box. Assuming steady-state, the turnover time or flushing time T of the estuary can then be estimated as

$$T = V / Q \quad (1)$$

where V is the water volume in the estuary and Q is the total freshwater input. In tidal estuaries, the amount of water exchanged at each tidal cycle is estimated as the difference of water volume between high and low tides, the so-called tidal prism V_p (Figure 8a). Using this tidal prism flushing model, a fraction

$$r = V_p / V \quad (2)$$

of the estuary water is assumed to be renewed by ocean water at each tidal cycle and the turnover/flushing time can be expressed as

$$T = \tau / r \quad (3)$$

where τ is the tidal period (e.g. 0.5 day for solar semi-diurnal tide and 1 day for solar diurnal tide).

The above models provide a very crude description of the exchange processes between the estuary and the coastal sea region. Very often, the net water exchange results from the difference between two opposite water fluxes corresponding to the inflowing sea water and the outflowing estuarine water. In the gravitational circulation model (Figure 8b), these water fluxes are associated with the two-layer

baroclinic circulation typical of partially mixed estuaries (Figure 7). In well-mixed broad estuaries, the two opposite fluxes can occur simultaneously in the horizontal plane (Figure 8c).

Figure 8. (a) The tidal prism box model (side view); (b) the gravitational circulation box model (side view); (c) the LOICZ box model for a vertically well-mixed estuary (plan view).

Using the configuration of the LOICZ model shown in Figure 8c, the steady state water balance in the estuary requires that the outflowing flux be the sum of the freshwater input in the estuary Q_r and the seawater inflow Q_d . Expression (1) of the turnover time can then be generalized with $Q = Q_r + Q_d$.

As steady-state, the rate Q_d can be calculated from the salt balance

$$Q_d \Delta S = Q_r S_{out} \quad (5)$$

where S_{out} is the salinity of the estuarine outflow and ΔS is the excess salinity brought by the seawater, i.e.

$$\Delta S = S_0 - S_e \quad (6)$$

where S_o is the salinity in coastal waters and S_e is the estuarine salinity. Setting $S_{out} = S_e$ leads to the

$$T_r = V/Q_r (1 - S_e/S_o) \quad (7)$$

The LOICZ method for the derivation of the renewal time is similar but S_{out} is taken as the mean salinity in the outer estuary, which is estimated as

$$S_{out} = 0.5 (S_o + S_e) \quad (8)$$

The LOICZ box model is simple and easy to use and has been used in about 200 estuaries worldwide. Rainfall, groundwater and evaporation can also be added if needed. If the system is not vertically well-mixed, a stacked box model can be used with a box on top representing the upper layer and a box on the bottom representing the lower layer and the vertical fluxes are calculated from salinity data.

The above box models, which can be further refined, are useful as a first approach but have serious limitations because they only capture some of the physics (e.g. Sheldon and Alber, 2006). they are all based on a steady state balance, assume complete and immediate mixing in the estuary, poorly account for the diffusive fluxes between the estuary and the coastal sea and ignore the spatial variations inside the estuary.

The flushing rate and the transport of pollutants also depend on the internal circulation within the estuary driven by the density difference generated by changes in salinity and temperature. This difference in density is determined by vertical mixing by the wind, by boundary-generated turbulence, and by turbulence in the water currents driven by tides, wind and river inflow. Vertical mixing is parameterized by the vertical eddy diffusion coefficient K_z , which is minimal at the level of the density interface (i.e. the pycnocline). Additional mixing also results from turbulence generated at the banks of the estuary and by secondary flows around shoals and islands, as well as 3-dimensional flows in meanders.

A proper description of estuarine dynamics and the assessment of the associated transport rates require therefore two-dimensional (either in the horizontal or in the vertical plane) or even three-dimensional models. Such models are elegant but they still carry uncertainties in term of the hydrodynamic conditions and the fate of tracers at the open boundaries as well as in quantifying the turbulent diffusion.

Also the influence of small scale features and the possible occurrence of **sandbanks** that fall **dry** at **low tide** require special numerical treatments. Unstructured grid models permitting local refinements of the computational mesh where necessary and taking into account external influences in a natural way are particularly suited for such studies (de Brauwere et al., 2011).

The refined description of the water circulation provided by high resolution numerical models gives also access to more representative transport timescales, namely the age, the residence time, the exposure time and the transit time, superseding the poorly defined flushing time, turnover time and renewal time. These timescales are best introduced by considering the fate of a water parcel or of a tracer particle (Figure 9).

Figure 9. Path followed by a particle in the estuary from the upstream boundary to the coastal sea. At time t , the age of the particle is $t - t_0$, its residence time is $t_1 - t$, its transit time is $(t_1 - t_0)$, its exposure time is $(t_1 - t) + (t_3 - t_2)$.

The age of a particle measures the time elapsed since it entered the estuary. The age reflects therefore the past history of the particle. With the residence time, one looks forward in time: the residence time is time necessary for a water parcel originally in the estuary to leave the domain for the first time. The exposure time is similar to the residence time but allows for particles to return into the estuary after leaving it (with reversing tidal currents, for instance) ; the exposure time of a particle originally in the estuary is the total time that the particle will spent in the estuary. The transit time of a particle is defined as the sum of the age and the residence time (Takeoka, 1984; Zimmerman, 1988).

Because of mixing, different particles introduced in the estuary at exactly the same location and at the same time will follow different trajectories and are therefore characterized by different timescales. Distributions of age, residence time, exposure time and transit time must therefore be considered, although one can usually content one-self with their average value in most cases.

The Constituent oriented Age and Residence time Theory (Delhez et al., 1999 and 2004) provides the appropriate framework to compute the above timescales in an Eulerian framework, in a suitable form to be easily implemented in existing numerical models. The mean residence time ϑ , for instance, can be obtained as the solution of the advection-diffusion problem

$$\frac{\partial \vartheta}{\partial t} + 1 + \nabla \cdot (\mathbf{v}\vartheta) + \nabla \cdot (\mathbf{K} \cdot \nabla \vartheta) = 0 \quad (9)$$

(where t is the time, $\mathbf{v}$ is the velocity and $\mathbf{K}$ is the diffusion tensor) with boundary conditions prescribing that ϑ vanishes at the open boundaries. To compute the exposure time, the same equation must be solved but the model domain must be extended offshore to describe the coastal circulation and describe the possible return path of tracers. Exact analytical solutions are available if the estuarine cross-section is constant along the channel, which is often a restrictive assumption.

Table 1 compares transport timescales computed using different approaches in various estuaries. Large differences between the various time scales exist for the same estuary, highlighting the importance of defining precisely the particular time scale needed for particular applications.

When the estuary is density-stratified, the residence time of water in an estuary also depends on the internal circulation within the estuary driven by the density difference generated by changes in salinity, temperature and suspended sediment concentration. This difference in density is determined by vertical mixing by the wind, by boundary-generated turbulence, and by turbulence in the water currents driven by tides, wind and river inflow. Vertical mixing is parameterized by the vertical eddy diffusion coefficient K_z , which is minimal at the level of the density interface (i.e. the pycnocline). Additional mixing also results from turbulence generated at the banks of the estuary and by secondary flows around shoals and islands, as well as 3-dimensional flows in meanders.

When the bathymetry is complex, e.g. with meanders or shoals, the water circulation in estuaries also varies markedly across the width, forming regions of convergence (where floating matter accumulates) or divergence (where floating matter disperses swiftly). This also modifies the water transport time scales.

Ecological implications of the transport time scales

For a given estuary the geomorphologic time scale determines the estuarine bathymetry. The habitats, including tidal wetlands and rocky zones, are determined by the underlying geology as well as the geomorphologic time and sediment transport time scales. The fate of nutrients and pollutants is determined by the habitats, and the sediment and water transport time scales. In turn all of these parameters determine the ecology of the estuary.

In a vertically well-mixed estuary, the nutrient is cycled between phytoplankton and resuspended microphytobenthos, zooplankton, bivalves and crustacea, and fish (Figure 10). Dying organisms, excreta, and left-overs from messy eaters become detritus that is recycled, some through the microbial loop. As shown by the dotted lines, tidal wetlands provide detritus and juvenile fauna to the estuary. This ecosystem is not closed, in fact it is supported by an inflow of nutrients, fish and plankton from the sea and the watershed (the river and groundwater); some of that matter is also lost by export to the sea. The level of processing of these various inflows depends on a large number of parameters including the climate, the habitats, the intensity of the inflows, the water and sediment transport time scales, and the partitioning coefficient. In turn the estuarine ecosystem is determined by these physico-chemical attributes and the ecological niches.

The same nutrient cycling may prevail in the top layer of a salt wedge estuary (Figure 11). However the situation is very different in the bottom layer, which is enriched by organic matter falling down from the top layer especially if the top layer supports an algal or plankton bloom. This organic matter decays in the bottom layer and extracts dissolved oxygen from the water column. As the bottom layer is not in contact with the water surface and the salinity stratification completely shuts down the turbulence at the salinity interface, oxygen cannot be supplied from the top layer. Oxygen can only be supplied by ventilation, i.e. the import of oxygen by currents bringing in oceanic waters in the bottom layer. This bottom layer becomes anoxic if

the oxygen consumption rate is larger than the rate of import of oxygen from oceanic water.

Partially mixed estuaries may suffer less from bottom water anoxia than salt wedge estuaries because the salinity stratification is less intense and does not completely shut down the turbulence; some vertical mixing remains and as a result additional oxygen is provided to the bottom layer by vertical diffusion of oxygen from surface waters.

Each of these physico-ecological relationships is affected by the human impact. A most common indicator of a severe human impact is that the bottom layer of vertically stratified estuaries – which has the largest water transport time scales - becomes anoxic or hypoxic. Estuaries with a small value of the water transport time scales have less time for the dissolved oxygen to be depleted and for sediments to accumulate in the estuary; such estuaries are thus intrinsically more robust than poorly flushed estuaries.

Another indicator of the human impact is the increasing frequency of harmful algae blooms. High riverine loads of Nitrogen and Phosphorus into an estuary initially lead to a bloom of phytoplankton or diatoms because their rate of uptake of nutrients is much larger than that by cyanobacteria. In nutrient-enriched estuaries located downstream of large dams that preferentially trap the fine sandy sediment, the phytoplankton or diatoms can exhaust the Silicate but not Nitrogen and Phosphorus; when that happens, cyanobacteria take over and harmful algae blooms can result. This situation is becoming common for many estuaries worldwide with a large water transport time scale and a large input of nutrients from sewage and fertilisers.

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Figure 10. (a) A typical pelagic food web in a vertically well-mixed estuary. It comprises a waterborne ecosystem (the blue box) that is moving with the water currents, thus comprising an inflow into the estuary and an outflow from the estuary; it is flushed at a rate determined by the water transport time scales. It comprises also suspended sediment that is also varying in time at a rate determined by the sediment transport time scales. It comprises also a benthos and bottom dwelling animals living in habitats that are varying in time at a rate determined by the geomorphologic time scale. (b) Typical salinity distribution increasing from the head to the mouth. The waterborne ecosystem (blue box) is advected seaward, thus remaining only in transient contact with the substrate and the tidal wetlands, and at the same time it is subject to increasing salinity as a result of mixing. As it moves towards the head of the estuary, the waterborne ecosystem also encounters different habitats.

Figure 11. A sketch of the water circulation in a salt wedge estuary. Organic detritus settles from the top layer where it is produced by an algal/plankton bloom. By decaying in the bottom layer this material extracts dissolved oxygen from the water column. Low dissolved oxygen commonly results in the bottom layer. If the inflow rate of dissolved oxygen by oceanic inflow in the bottom layer is smaller than the consumption rate of dissolved oxygen by the decay of organic matter in suspension and on the bottom, anoxia can result.

Table 1: Example of the water transport times (in days) for various vertically fairly well-mixed estuaries.

	Renewal time (LOICZ box model)	Average residence time (CART, 1D)	Average exposure time (CART, 1D)	Average residence time (2-D numerical model)
CURIMATAÚ ESTUARY (BRAZIL)				
NEAP TIDES	0.5-0.9	0.1-0.6	1.2-1.7	-
SPRING TIDES	0.5-1.4	0.02-0.1	1.4-2.2	-
HUDSON ESTUARY (USA)				
NEAP TIDES	4.3-5.3	1.2-2.3	6.2-6.7	8-10
SPRING TIDES	4.2-5.2	1.3-2.3	10.1-11.2	8-9
CONWY ESTUARY (UK)				
NEAP TIDES	31.8-35.3	10.2-12.8	74.6-81.1	-
SPRING TIDES	28.1-31.2	6.0-7.7	109.5-120	-
MERSEY ESTUARY (UK)				
TYPICAL FLOW RANGE	3.5-7.8	0.5-1.7	35.4-99.5	1-6.3
SCHELDT ESTUARY (BELGIUM-THE NETHERLANDS)				
AVERAGE CONDITIONS	23.8-75.2	5.3-10.4	204.1-302.5	5-70

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