MANAGING FRESHWATER INFLOWS TO ESTUARIES

Lost to the Tide: The Importance Of Freshwater Flow To Estuaries

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“LOST TO TIDE” - THE IMPORTANCE OF FRESH WATER FLOW TO ESTUARIES

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A distressing conflict has emerged over two of water’s roles: as a commodity serving the aims of greater agricultural productivity, industrial expansion, and urban growth, and as a key life-support for all species and communities. Mounting scarcity has thrown this friction into sharp relief.
Sandra Postel (1992)

There is an old joke among hydrologists that water always runs downhill toward the sea, except where it runs uphill toward money. While it is true that the attractions of wealth and the pull of politics combined with pumps and fossil fuel can delay the inevitable victory of gravity, the most recent assessments of the global cycle of fresh water confirm that about $40 \cdot 10^{12}$ m^3 y^{-1} of fresh water continue to flow from the continents to the sea, an amount essentially in balance with the amount of water that evaporates from the ocean and falls on land as rain and snow (Jackson et al. 2001, Dai and Trenberth 2002). The construction of some 40,000 large dams over 15 m high plus perhaps 800,000 smaller dams (Oud and Muir 1997) has not altered this balance. Moreover, the amount of water stored on land behind dams ($6.6 \cdot 10^{12}$ m^3, Postel 1999) has approximately balanced the amount of very old groundwater that has been withdrawn from deep aquifers and added to the sea (Vörösmarty and Sahagian 2000). If anthropogenic interventions in the hydrological cycle of this scale have not altered the flow of fresh water to the world’s coasts, why are increasing numbers of coastal ecologists concerned with the looming crisis in global fresh water supplies? It is not because they are worried about the total volume of fresh water reaching the sea.

While there is convincing evidence that human population growth, increasing consumption rates and, to a lesser extent, climate change, will lead to severe shortages of fresh water in many parts of the world during the next 25 years (Vörösmarty et al. 2000), there is no reason to believe that the total flow of fresh water to the ocean from land will decrease. Water withdrawn for irrigation will largely evaporate and return to the land or coastal sea as precipitation. Water consumed by livestock will return to the landscape as metabolic waste, and water consumed by humans will be excreted on the landscape or, increasingly, returned by sewer systems to rivers or the sea. Industrial withdrawal for cooling or washing will be returned quickly to rivers or products will be consumed and the water returned to the environment at another time and place. Moreover, the mining of deep ground water aquifers will almost certainly continue while the rate of new dam construction will slow (Vörösmarty and Sahagian, 2000). The current rate of new dam closure is about 250 each year compared with about1000 each year during 1950 – 1970 (data of P. McCully cited by Jackson et al. 2001). As a result, it is likely that more fresh water will flow from land to the ocean than has been the case during the last fifty years. The projected melting of glacial ice will, of course, also add fresh water to the ocean and may impact coastal areas in high latitudes.

Why Are Coastal Ecologists and Managers Concerned About Fresh Water?

There is a simple reason why coastal ecologists and managers are increasingly concerned that continued construction of dams (albeit at a more modest rate than in recent decades) and other water structures to serve human needs and desires will have an adverse impact on the diversity and productivity of coastal marine waters. While at global, regional, and continental scales the flux of fresh water from land to the sea may remain relatively unchanged or even increase, the amount of fresh water flow locally varies enormously among the world's thousands of watersheds depending on their size, climate, and land cover (eg. Dai and Trenberth, 2002). And there is no question that water projects can dramatically alter the export of fresh water from individual watersheds to the sea (Vörösmarty and Sahagian 2000). The consequences of changing the inflow of fresh water to an estuary, the place where a river mixes with the sea, can be profound, including losses of wetlands, declines in fisheries, and accelerated coastal erosion (Halim 1991). As noted by Montagna et al. (2002), "Nothing is more fundamental to the functioning of an estuary than the quantity and timing of freshwater delivery...."

Water projects can alter the delivery of fresh water to estuaries in three ways:

- First, the total amount of fresh water flowing to the estuary over an annual cycle may be changed by water use within a watershed or by diversions between watersheds. For example, the creation of large reservoirs and the introduction of irrigated agriculture both increase evaporation and the loss of water to the atmosphere. The lost water will return to earth as precipitation, but it may fall in other watersheds. Water may be taken from a river in one watershed and piped into another watershed where it is used for human or industrial use and then discharged as wastewater in that watershed.
- Second, seasonal variations within the annual cycle of flow may be seriously disrupted. Human uses favor storage of flowing waters with dams for flood control and stable water and hydropower supplies, straightening of meandering surface waters for efficient navigation, and drainage of slow moving or standing water for agriculture and development. Dams are designed to reduce or eliminate variations in flow; navigation channels deliver water very quickly under flood conditions; and drained wetlands provide neither flood storage nor a source of water during low flow conditions. Natural river and estuarine systems have adapted to pulses of high and low water delivery that are damped by the long transit times of meandering streams and rivers and the slow release of sheet flow storage from wetlands.
- Third, the composition of the water released from a watershed is a reflection of the human uses of the water and the land in the system. Obviously, the discharge of sewage and the inflow of agricultural drainage alter the chemistry of the receiving rivers and streams, but the storage of water behind dams also influences the chemistry of the water that is allowed to pass the dam and markedly reduces the amount of

sediment transported to the coast (Vörösmarty et al. 1997, Ittekkot et al. 2000, Nixon 2003). The composition of the water is also modified to some extent by the rate of flow of water through the watershed. For example, if water moves rapidly through the system, the removal of nitrogen through biological uptake and storage and denitrification may be reduced (Howarth et al. 1996). Thus, there is a strong and inescapable link between water quantity and water quality (Pinay et al. 2002).

The coupling between fresh water flow and downstream estuarine ecology is not always recognized because the social drivers of water projects and the stakeholders involved with estuarine resources are different and separated geographically. There is also little tradition of collaboration and communication between scientists and managers of fresh water systems and those who study and protect coastal marine environments.

While there appears to be a growing recognition of the historical and potential future negative impacts of water development projects of the ecology of river and stream ecosystems (Gleick 2000, Pinay et al. 2002, *the Environmental Flows IUCN thing, some nature Conservancy stuff*), there is less awareness of the much more complex role of fresh water inflow in estuarine ecology. For example, in an otherwise excellent review of water issues, Jackson et al. (2001) devoted only one sentence to coastal impacts and that was focused on water quality and eutrophication concerns. In their policy forum on Managing Water for People and Nature in *Science* magazine, Johnson et al. (2001) did not mention estuarine and coastal impacts of fresh water management projects.

Given the common lack of interaction and integration between fresh water managers and coastal managers and between river ecologists and estuarine ecologists, it is not surprising that those involved with the design and construction of fresh water projects often speak of fresh water that reaches the sea as "lost to tide" or "wasted." Our purpose here is to contribute to what we hope will be a growing dialog among these groups. The purpose of such dialog is to add the fresh water needs of downstream estuarine ecosystems and their resources to the complex of considerations that enter the design and operation of fresh water projects. A common understanding of the importance and role of fresh water in estuarine ecology seems an important first step. The projected demands for fresh water in much of the developing world during the coming decades suggest that there is no time to lose.

What Are Estuaries and Why Are They Important?

In an introductory chapter to one of the first major books devoted to the science of estuaries, Pritchard (1967) defined them as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water from land drainage." Estuaries are the places where fresh water links land and sea and creates unique types of ecosystems adapted to such things as varying salinities, high sediment concentrations, changing depths, relatively strong tidal currents, large inputs of nutrients, and migrating populations of animals. They are also places where other types of energy combine with sunlight to enhance biological metabolism so that large yields of fish and shellfish can be harvested and many of society's wastes products can be decomposed. They are often places of great beauty and hubs of commerce and trade.

There are various types of estuaries and ways of classifying them, depending on their shape, salinity, physical circulation, and major stresses and energy sources (eg. Odum et al. 1974, Kjerfve 1989). On the most basic level, we recognize two different types – river mouth estuaries and coastal lagoons. River mouth systems are usually aligned perpendicular to the coast and may have relatively deep channels and complex islands or deltas at the mouth. On coasts that were once glaciated, some river mouth estuaries may have a sill or shallow barrier near the mouth. These are called fjords and have very restricted circulation of their bottom waters. Very large rivers, such as the Amazon, and some smaller rivers during periods of flood may have no estuary because the flow of fresh water is so great that no salt water can penetrate into the river mouth. In this case, all of the fresh and salt water mixing takes place on the open continental shelf rather than within "a semi-enclosed" area. Coastal lagoons are very shallow systems of a few meters depth that are usually aligned parallel with the coast. They are commonly separated from the open sea or from a larger river mouth estuary by barrier spits or islands, though as in the case of South San Francisco Bay, they can also be formed by tectonic processes. The connection between lagoon estuaries and the sea may be permanent (often stabilized with engineered jetties) or intermittent as the passes between barrier islands open and close. There may be one or several inlets. The connection with the sea may be quite restricted in some lagoons and direct groundwater discharge rather than surface flow may be the most important source of freshwater in lagoons. In tropical areas, coral reefs may form the barrier setting off a coastal lagoon, but only where fresh water flow is small and there is a vigorous exchange with the sea, because corals require high and relatively constant salinity. They also require high light levels and therefore do not do well where rivers discharge large amounts of colored dissolved organic matter or suspended sediment.

Estuarine Productivity

Regardless of whether they take the form of river mouths or coastal lagoons, estuaries almost universally share a common high rate of production of plants and animals. As E.P. Odum wrote in his classic *Fundamentals of Ecology* (1971), "Characteristically, estuaries tend to be more productive than either the sea on one side or the freshwater drainage on the other." It is this high productivity that has attracted people to estuaries for thousands of years. While large scale industrial fisheries are now directed largely at continental shelf and open sea resources, estuarine landings continue to be important throughout the world, especially in countries that remain dependent on lower technology and artisanal fisheries (eg. Ruddle and Johannes 1985).

The high productivity of estuaries is often illustrated by tables summarizing the weight per unit area of plant material produced in salt marshes or mangrove forests over an annual cycle compared with the weight of corn or other crops harvested per unit area of agricultural land. But most of the primary or plant production in most estuaries is carried out by unicellular algae suspended in the water, the phytoplankton, rather than by larger rooted plants. Again, however, comparisons of the amount of carbon fixed by photosynthesis of the phytoplankton in estuaries compared with the phytoplankton of the open sea provide impressive evidence of the higher rates found in most estuaries. [*Text box showing comparisons*] Important exceptions are estuaries where the rivers carry very large amounts of sediment or high concentrations of colored dissolved organic matter (sometimes called “black rivers”) and light can not penetrate to any significant depth in the water.

Harvests of animals and the high quality protein they contain are also much higher from estuaries than those provided by unmanaged terrestrial systems or temperate fresh water lakes (Nixon et al. 1986, Nixon 1988). Since almost all meat production is now based on agriculture, it is more difficult to make comparisons such as those for mangroves and corn, but some anthropological and historical data can be used to make the point. For example, harvests of meat by Algonquian hunting bands in historical Canada were probably less than 1 kg $ha^{-1}y^{-1}$ (Knight 1965) and free range cattle production by the Dodo People in Uganda are on the order of 10 – 15 kg ha^{-1} y^{-1}, including milk and blood (Deshler 1965). Even common pastures under minimal management in what is now southern New England in the United States were only yielding 25 – 50 kg ha^{-1} y^{-1} of meat, cheese, and butter around 1700 (Bidwell and Falconer 1941). Temperate lakes commonly yield less than 10 kg ha^{-1} y^{-1} of fish (Ryder et al.1974, Schlesinger and Regier 1982, Nixon 1988). Intensively fished temperate estuaries, however, often yield hundreds of kg ha^{-1} y^{-1} of fish and shellfish, values matched only by upwelling systems and some intensively fished tropical lakes (Nixon 1988).

Why Are Estuaries So Productive?

Because estuaries are usually protected from waves and strong currents compared with open coasts, and because estuaries may receive large amounts of sediment from rivers and streams, they are often characterized by extensive intertidal wetlands with associated tidal channels that provide important habitats for fish and crustaceans as well as water fowl. These intertidal wetlands are dominated by different types of plants depending on latitude, salinity, and tidal range, but they share common high rates of photosynthesis and growth. The intertidal systems are fertilized by nutrient rich sediments carried down to the estuary from the watershed by rivers and delivered to the wetlands by high river flows and by tidal currents. While little of the plant material produced by the wetlands is consumed while it is green, all of these intertidal communities, whether salt marshes or brackish marshes or mangroves, produce large amounts of detritus or dead organic matter that it enriched by bacterial and fungal growth as it decomposes. This detritus may provide an important food source for estuarine and near shore animals.

The shallow depth of estuaries is also important in stimulating their high rates of production. Being shallow is important for at least three reasons:

- Especially in lagoons, where there is less sediment input from large rivers and depths are particularly shallow, light often penetrates to the bottom and supports the growth of a diverse mix of types of plants, including flowering rooted plants or sea grasses, microscopic algae that grow on the sediment surface and on the sea grass leaves, and larger algae or "seaweeds" that drift along the sediment surface or grow attached to harder substrates or on seagrass leaves, as well as the single celled phytoplankton that must provide all the production in deep waters. The larger plants provide structure for nursery areas and protection from predators as well as food. It may also be important that they change more slowly in abundance than the phytoplankton and provide a stability of resources that plankton dominated systems lack.

- In deep water, primary production by the phytoplankton is confined to the sunlight surface layer. As organic matter sinks slowly through the water, it is continually diluted and consumed and only a small fraction reaches the bottom in very deep waters. In shallow systems, there is less volume below the productive zone to dilute the organic matter so animals do not have to expend as much energy searching for food. More importantly, the shallow floor of an estuary receives a large portion of the production where it is concentrated for bottom dwelling organisms and their predators.
- Since the bottom captures or receives a large fraction of the organic production in shallow systems, it is also where much of the regeneration of nitrogen, phosphorus, silica, and other nutrients takes place as bottom living animals and microorganisms consume the organic matter. Because the heterotrophic or regenerative part of the ecosystem is in close proximity to the autotrophic part (the sunlit surface water where organic matter is formed), nutrient cycling can be rapid and efficient. The rapid return of nitrogen, phosphorus, and silica to the water where light is abundant allows for high rates of carbon fixation even when nutrients are in short supply.

The location of estuaries at the "bottom" of watersheds is also important in stimulating their high rates of production. Unfortunately, it also puts them at particular risk from pollution generated in the watershed. Watersheds are commonly many times larger than the estuaries they feed. As water flows increase from primary to secondary to higher order streams and rivers at lower elevations, the amount of nitrogen and other nutrients draining from the land also accumulates, and the burden of other anthropogenic pollutants may also increase as the fresh water nears the sea. In some ways, the relationship between the watershed and its estuary is the reverse of that between a smokestack and the atmosphere. A smokestack takes highly concentrated pollutants and disperses them into a large volume of air. The natural flow of a watershed concentrates dispersed sources of nutrients and other materials and discharges them into a smaller area, the estuary. As a result of this process (and the dense human populations that often cluster on the shores of estuaries), the flow of nitrogen and phosphorus to estuaries is higher per unit area than it is to some of the most intensively fertilized agricultural land (Nixon et al. 1986). In some cases, this fertilization stimulates high rates of primary and secondary (animal) production. In other cases, fertilization may lead to too much primary production and to problems of low oxygen (hypoxia) or no oxygen (anoxia) in the bottom water or to other undesirable consequences (Rabalais and Nixon 2002). The impact of the nutrients for good or ill may depend to a large degree on the extent of tidal mixing in the estuary (Nixon and Buckley 2002).

The importance of tidal mixing in estuaries is due to their shallow depth. The vast majority of the tidal energy of the world oceans is dissipated on the shallow continental shelves and in coastal areas where tidal currents are accelerated and frictional interactions of the currents with the bottom become very important (Mann and Lazier 1996). In estuaries and other shallow areas that provide some of the world's most productive fishing banks, strong tidal currents provide a lot of mechanical energy that mixes the water. This is particularly important in estuaries because of their fresh water input. Fresh water is less dense than salt water and tends to float on the surface when it reaches the sea. A positive aspect of this is that the nutrients the river water may contain will be in water that receives a lot of light and phytoplankton growth may be rapid. The negative aspect is that when the water is strongly stratified with depth (a big difference in salinity or temperature between the surface and the bottom), the bottom water is not exposed to the atmosphere. As organic matter formed in the surface water sinks to the bottom, it will be consumed by animals and microorganisms in the bottom water and in the sediment. As the organic matter is consumed and respired, the oxygen contained in the bottom water will also be consumed. Unless the bottom water is brought to the surface, all of the oxygen will eventually be consumed (often in a matter of a few days), toxic hydrogen sulfide may accumulate, and organisms will die. Mixing by the tides and wind usually prevents this from happening, except when inputs of fresh water are very large and tidal currents are weak or there are prolonged periods with little or no wind. As increasing amounts of nutrients have been added to some estuarine and coastal areas in recent decades, the growth of phytoplankton in these areas has increased so much that the tidal and wind mixing that once provided oxygen to the bottom water are no longer adequate and hypoxic or even anoxic conditions have developed.

The interaction of fresh water inflow with nutrient delivery, vertical density stratification, and loss of oxygen from deeper waters is an excellent example of the complexities inherent in dealing with fresh water in estuarine systems. Fresh water brings life stimulating nutrients that fertilize the estuary, but it also can "put a lid" on the estuary that separates the saltier bottom waters from the atmosphere and thus leads to low oxygen conditions and possible death for bottom organisms. Without nutrients, there can be no production of plants and animals. With too much fertilization, tidal and wind mixing can be overwhelmed and low oxygen conditions produced. Withdrawing fresh water from an estuary can reduce nutrient inputs and perhaps increase vertical mixing, but production may decrease. Water diversions from one watershed to another and large pulses of fresh water addition from dam operations may increase vertical stratification and lead to problems with hypoxia and anoxia.

In addition to their role in mixing the water, tidal currents contribute to the productivity of estuaries by bringing nutrients, dissolved gases, and food to estuarine plants and animals that remain fixed in place. This energy subsidy is important in sustaining intertidal marshes and mangrove forests as well as dense meadows of sea grasses and kelp beds. It is also critical for supporting many filter feeding bottom animals. Without tidal currents spectacular concentrations of animals such as those found in estuarine oyster and muscle reefs would be impossible because large masses of animals require the plant production from large areas for food. The lack of significant tidal currents in lakes may be an important reason why they are less efficient at producing animals than estuaries are (Nixon 1988).

Why is Fresh Water Inflow Important in Maintaining Estuarine Productivity?

We have already noted that fresh water delivery to estuaries may be important in maintaining their productivity because of the sediments and nutrients that are carried by the water. The former helps to build and sustain intertidal wetland habitats and the latter stimulates plant production of all types. Another obvious contribution of fresh water input is that it may make it possible for important species of anadromous fish such as salmon, shad, and eels to pass through the estuary during their spawning migrations. But fresh water also plays a much less obvious and more complex role in estuarine production.

Fresh Water Input and Estuarine Circulation

Just over fifty years ago, Pritchard (1952) (the same man who would later define estuaries) published the first scientific description of the remarkable role that fresh water input plays in the physical circulation of estuaries. Based on work in Chesapeake Bay, he showed that the less dense fresh water entering at the head of an estuary floats on top of the denser sea water. As the less dense fresh water flows "downhill" toward the sea over the saltier water, some mixing occurs. As a result, some salt water is mixed up into the seaward flowing surface layers. This salt water is discharged at the mouth of the estuary along with the fresh water. The salt water that is lost with the surface flow is replaced by a landward flow of sea water. This pattern of seaward flowing, less salty surface water and landward flowing, higher salinity bottom water is often called "estuarine circulation." It is also known as "buoyancy driven circulation" or "gravitational circulation," but by whatever name it is an important feature of coastal areas where fresh water input is significant and tidal mixing is not so strong as to eliminate the vertical salinity gradient.

One of the surprising aspects of estuarine circulation is that the flow of coastal sea water it brings into an estuary is often much greater than the volume of river flow. A simple example can illustrate this principal. Suppose an estuary receives river flow amounting to 100 m^3s^{-1} and (as is commonly observed) that the surface water flowing out the mouth of the estuary is only slightly less salty than the adjacent ocean. In this case, let us assume that the ocean has a salinity of 34 parts per thousand (ppt) and that the surface water flowing out of the estuary has a salinity of 30 ppt. It is clear that most of the surface outflow must be sea water. In this case, it would require a landward flow of 750 m^3s^{-1} of sea water to replace that being lost with the 100 m^3s^{-1} of fresh water. We know this because we can calculate the volume of 34 ppt water required to mix with 100 m^3s^{-1} of 0 ppt water to produce a salinity of 30 ppt in the departing surface water:

$$\underset{\text{(fresh water)}}{\text{Volume} \bullet \text{Salinity}} + \underset{\text{(sea water)}}{\text{Volume} \bullet \text{Salinity}} = \underset{\text{(departing surface water)}}{\text{Volume} \bullet \text{Salinity}}$$