Chapter 2
Conceptual Model of Estuary Ecosystems

2.1 Estuaries

An estuary is a semienclosed 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 (Pritchard 1967). Most estuaries have a series of landscape subcomponents: a river (or fresh water) source, a tidal-estuarine segment, marshes (or mangroves depending on latitude), bays, and a pass (or inlet) to the sea. However, all estuaries are quite different; the landscape of each subcomponent can vary, combinations and connections of these subcomponents can vary, and some subcomponents can be missing. The interaction of three primary natural forces causes estuaries to be unique and different:

- Climate—causing variability in the freshwater runoff and evaporation regimes.
- Continental geology—causing variability in elevation, drainage patterns, landscapes, and seascapes.
- Tidal regime—causing differences in the degree of mixing and elevation of the mixing zone.

Because each of these three physical drivers can vary in a large number of ways, it is easy to imagine how the various combinations of these forces can combine to create a vast array of estuarine typologies. Further variability in estuarine typology is caused by the interactions of these physical drivers.

The physical differences among estuaries are the key to predicting the effects of fresh water alterations. Thus, classifying estuarine typologies is an important first step toward understanding the need for riparian connections to the sea. In spite of the unique signatures of most estuaries, several classification schemes have been presented (Pritchard 1967; Davies 1973; Day et al. 1989).

Based on geomorphology, Pritchard (1952) recognized four estuary typologies: (1) drowned river valleys created by sea level change or sediment starvation in coastal plains, (2) fjords formed by glaciations, (3) bar-built estuaries formed by sediment deposition by winds and tides, and (4) tectonic estuaries caused by

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faults in the coastal zone. Davies (1973) recognized that there is a continuum of inlet types based on the energy expended on the coast by waves. On one end of the spectrum are lagoons that are enclosed by sandy spits and at the other end of the spectrum are deltas that are muddy and formed by river processes. Day et al. (1989) recognized that all previous definitions still do not encompass all estuarine typologies and suggested that an estuary is any coastal indentation that remains open to the sea at least intermittently and has any amount of freshwater inflow at least seasonally.

Water balance is the second important defining characteristic of estuaries. The freshwater balance is simply the sum of the water sources minus the sum of the water losses. The many sources of fresh water to the coastal zone include: rivers, streams, groundwater, direct precipitation, point-source discharges, and non-point-source runoff. There are fewer mechanisms that cause losses of fresh water, but these primarily include evaporation and freshwater diversions for human use. Pritchard (1952) recognized three classes of estuaries based on natural hydrological processes: (1) positive estuaries where freshwater input from rain, runoff, rivers, and groundwater exceeds evaporation; (2) neutral estuaries where the sources and losses are in balance; and (3) negative or inverse estuaries where evaporation exceeds the combined sources of fresh water. Depending on climate, some systems change seasonally, being positive during rainy seasons and negative during dry seasons. Many estuaries in the world have strong year-to-year variability caused by interannual climatic variability.

2.2 Human Interactions

Human activities and water resource development can change the freshwater balance in estuaries dramatically (Fig. 2.1). Freshwater diversions used as water supplies for large humans populations or large agricultural areas are large sinks or losses to systems. However, return flows (e.g., wastewater or industrial water) add a source of fresh water to ecosystems. In many cases, the diversions and return flows can be roughly in balance if they are planned as a unit using integrated water planning. But this is rarely, if ever the case. Because many water systems depend on gravity feeds to save pumping expenses, diversions are often taken upstream and returns (minus losses to leaks and use) are put in downstream. Depending on intervening elevation and geomorphology, return flows can even be put into different watersheds. When the demand for water is large relative to the supply, the water balance can be altered significantly.

Clearly, the estuaries most at risk from human activities are those that already have a negative water balance throughout the year or during certain seasons or times. Those estuaries that are neutral but have large upstream water demands are also at great risk of degradation due to altered flow regimes. The change of fresh water volume will have profound effects on salinity in a shallow estuary (e.g., coastal plain estuaries or lagoons), but a smaller effect on a deeper estuary

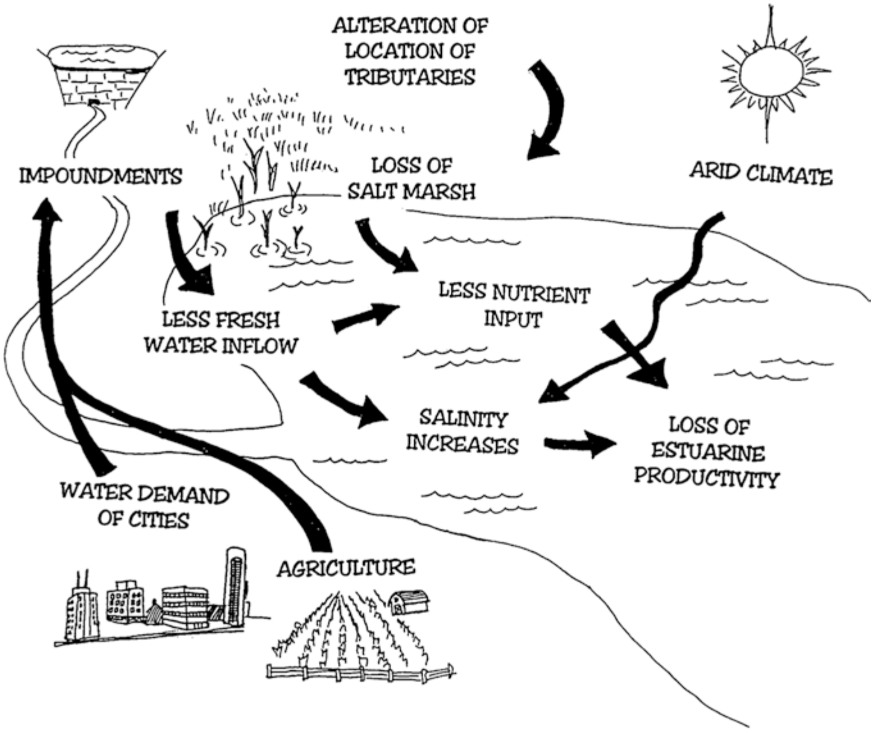

Fig. 2.1 Effects of altered inflow on estuaries (Montagna et al. 1996)

(e.g., fjords or tectonic estuaries). This difference of effect is often caused by shallow estuaries having smaller water volumes than deeper estuaries.

Given that humans can now alter many factors of the water cycle, it is imperative that freshwater resources be managed effectively to protect downstream ecological resources. Beginning in the 1960s, scientists began to investigate how altered freshwater flows to the coast might affect biological resources (Copeland 1966; Hoese 1967). Since then, there have been at least two major compilations of papers on the topic: Cross and Williams (1981) and Montagna et al. (2002a). As a result of these two symposia and other work there have been two important reviews (Alber 2002; Estevez 2002) from which a conceptual model has emerged that helps us to identify inflow effects (Fig. 2.2).

Following a review of the practices in three states (California, Florida, and Texas) where there is a long history of inflow studies, Alber (2002) defined the scientific framework for identifying the effects of inflow on estuarine resources. Historically, all freshwater inflow methodologies started from the perspective of hydrology or resource protection. The earlier approaches were all focused on resources such as protection of fish, charismatic, or iconic species. The problem quickly encountered is that the relationship between biology and hydrology is

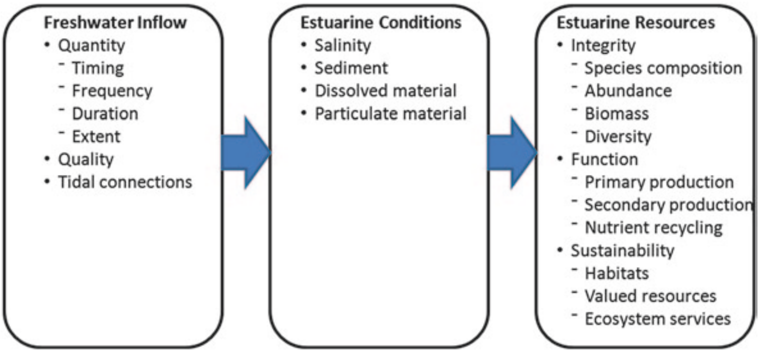

Fig. 2.2 Conceptual model of inflow effects (modified from Alber 2002)

complex and embedded in the food web and material flow dynamics of estuaries. For example, one cannot grow fish by simply adding water to a fish tank. These experiences led to a generic framework where inflow hydrology drives estuarine condition and estuarine condition drives biological resources (Fig. 2.2).

Ultimately, biological resources in estuaries are affected by salinity more than flow by itself. Salinity is affected by flow, but there are complexities because of the interactions between tides and geomorphology. Consequently, all salinity-flow relationships are characterized with very high variance or scatter, especially in the low flow end of the spectrum. Because of the links among flow, salinity, and biology, all the resource based approaches are multistep. First, the resource to be protected is identified. Second, the salinity range or requirements of that resource are identified in both space and time. Third, the flow regime needed to support the required distribution of salinity is identified, usually using hydrodynamic and salinity transport models.

The usefulness of the environmental flow framework (Fig. 2.2) is that estuarine resources are categorized into the familiar framework used to describe ecological health (i.e., integrity, function, and sustainability). Two new terms are added: valued resources and ecosystem services. The resources are typically called “valued ecosystem components” or VECs. These are resources that are identified by stakeholders as having esthetic, ecological, economic, or social value. These resources include bioengineers (or foundation species) that create habitat, fisheries species, and birds. These species are typically charismatic, characteristic, or iconic to an area. Ecosystem services are the benefits provided by the environment to human health and well-being (Costanza et al. 1997). It is clearly in the socioeconomic interest to sustain ecosystem services, especially those provided by VEC habitats such as oyster reefs, marshes, and seagrass beds.

Another important feature of the environmental flow conceptual model (Fig. 2.2) is that it is analogous to the well-accepted environmental risk assessment (or risk management) paradigm (Fig. 2.3) that has evolved in water quality management since the 1970s. The risk assessment paradigm is also known as the pressure-state-response (PSR) model. In the water quality PSR model, the pressure is applied from a toxic substance, the state represents the presence or

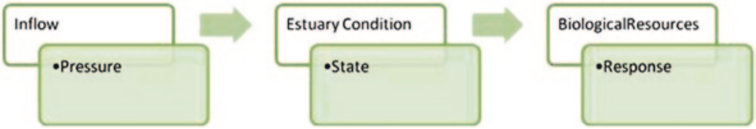

Fig. 2.3 Relationship between conceptual model of inflow effects and the water quality risk assessment paradigm

concentration of a substance, and response is the biological response to that state. Management actions are another way in which "Response" can be thought of. The analogy here is that flow is the pressure, estuarine condition is the state, and change in estuarine resources is the biological response (Fig. 2.3). This is a very powerful way to think about the effects of inflow on estuarine resources, because it helps us to define the ecological health of estuaries. Assessing risk by defining health is often the first step in managing environmental resources.

Defining Ecological Health

- Ecological health is assessed by determining if <u>indicators</u> of ecological <u>conditions</u> are in an acceptable range.
- Indicators are measures (or metrics) of ecological health for which sufficient information exists to establish an acceptable range of responses across broad spatial and temporal scales.
- Ecological condition is the status of ecological <u>function</u>, <u>integrity</u>, and <u>sustainability</u>.
- Ecological function is judged acceptable when the ecosystem provides important ecological processes.
- Ecological integrity is acceptable when the ecosystem has a balanced, resilient community of organisms with biological diversity, species composition, structural redundancy, and functional processes comparable to that of natural habitats in the same region.
- Ecological sustainability is acceptable when an ecosystem maintains a desired state of ecological integrity over time.

Defining ecological health is a vexing issue. Consider the analogy with human health. Scientists have proven that the normal human body temperature range is 36.4–37.2 °C. If a person's body temperature is above this range then they have a fever, and are likely sick. This example illustrates several important principles about human health as it relates to defining ecological health and how the definition has evolved for water quality assessment (Montagna et al. 2009). It is easy to integrate the conceptual model of inflow effects and the risk assessment paradigm to provide a general reference frame to define "ecological health" (see Box). Indicators of health have to be identified and the indicators must be within an acceptable range. Two difficulties are that there are no simple indicators of ecological health; and when an indicator can be measured, there are seldom sufficient data to know what the acceptable ranges are. Also, the definition of ecological health is complex because it depends on definitions of other terms (those underlined terms in the box). But in the end, the most important indicator is likely ecological sustainability. Sustainability is the ultimate definition of ecological health because an environment that is sustainable is healthy in the strict sense.

2.3 Hydrology and the Water Cycle

Water is the most widely used natural resource on the Earth. However, less than 1 % (0.7 %) of the water on the Earth is fresh and of sufficient quality to be classified as drinkable. Only two-one thousandths of 1 % (0.00002) is readily available in streams and lakes for humans to use to drink, bathe, or irrigate crops. The same amount of water is available today as 2,000 years ago, yet the world's population was just 3 % of what it is today, thus water availability is an extreme limit to growth and prosperity (Lane et al. 2003).

The Earth is often referred to as the blue planet because water covers about two-thirds of its surface. Because water is so plentiful on the Earth, the water cycle influences most climatic and surface geologic processes. Two dominant processes drive the water cycle: evapotranspiration and precipitation (Fig. 2.4). Water resource planners, however, appear to be concerned mainly with precipitation because they can manipulate runoff. Rain over large areas interacts with land elevation to form drainage patterns and familiar landscapes, e.g., tributaries, streams, rivers, and wetlands. These drainage systems are watersheds. If the

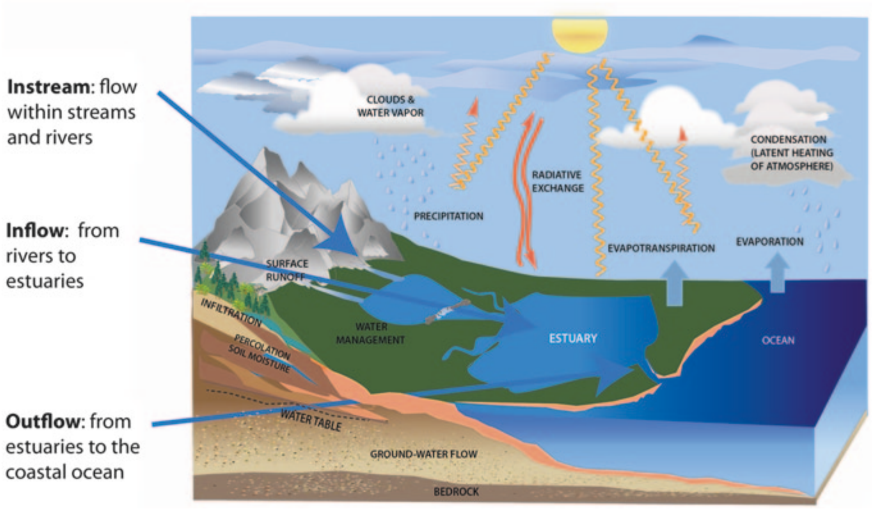

Fig. 2.4 Locations of environmental flows in the water cycle

watershed is adjacent to the coastal zone, then the ultimate drainage basin is the estuary, where fresh water mixes with sea water. Freshwater runoff can, and has been, manipulated to develop hydroelectric power or create reservoirs for water storage. Altering watercourses alters riparian, wetland, and estuarine habitats (Fig. 2.1). In coastal regions, the effect of freshwater inflow alteration depends on the type of estuary, the biological components present, and the climatic setting.

It is important to be able to build water budgets in order to manage flow to estuaries. In most places in the World, there are already abundant data on water flow and availability because of the importance of water to agriculture, cities, and industry. However, rainfall and river flow alone are not always sufficient to calculate total inflow to estuaries. Fresh water can also enter estuaries via runoff from land and through seepage of ground water. The degree to which these are important will likely be unique to each system. Initially, runoff and ground water seepage can be assumed to be small or insignificant, but eventually estimates of these inputs will be needed. Runoff is usually calculated based on models of land elevation, drainage patterns, and rainfall. Unlike surface water, ground water is difficult to observe and measure. Runoff estimates are found commonly, but groundwater inputs are rarely used in water cycle planning budgets.

Evapotranspiration is the water loss from direct evaporation of the water surface and water lost through plants. Water loss from a system due to evapotranspiration must also be known, especially in hot, dry areas where the volumes can be large. Evaporation can be measured directly by placing water in a pan and measuring the volume lost daily. Total water loss can be calculated as the product of the evaporation rate and the surface area of the water body.

Human activities and water use and reuse must also be accounted for. Water authorities usually record the amount of water withdrawn from ecosystems for human use, thus it should be relatively easy to obtain this information over a long period of time. Water is also returned to the environment after use. This is usually in the form of wastewater, but sometimes it is agricultural runoff, or industrial cooling water. These quantities should also be known and accounted for in determining the total inflows to estuaries.

Once all the basic parameters are known, the water balance can be calculated. The water balance for an estuary is simply the sum of the inputs, minus the sum of the outputs:

$$\begin{aligned} Water\,balance = &(precipitation + river\ flows + runoff + return\ flows) \\ &- (evaporation + diversions) \end{aligned}$$

In this case, precipitation is directly falling on the surface of the estuary. This value will be small and insignificant in drowned river valleys, but large and significant in large coastal bays.

The natural hydrological parameters (i.e., rain, inflow, runoff, and evaporation) are driven by climate, which varies considerably within years (i.e., seasons) and among years. It is clear from the recent debate on climate change that different climatic cycles range from decades to millennia. The natural variability in river flow and levels is essential information to know for water resource management.

In the end, environmental flows are likely most beneficial if they mimic the natural flow regime. The regime is composed of several characteristics including the variability of flow rates and levels. Storms create floods, which in turn create events that drive change in ecosystems. The size of these events (or disturbances) has several important characteristics: frequency, duration, extent, and timing. Each of these characteristics will have a statistical distribution with a mean and variance. Frequency is how often flood events occur. Duration is how long the event lasts. Extent is the magnitude or size of the event. Timing is the seasonality of events. For example, during a recent demonstration project to divert flow back into a marsh restoration area, the frequency, timing, and duration of floods was restored; but the extent was not because large volumes of water were trapped behind a dam (Ward et al. 2002). This project demonstrates that all characteristics of freshwater inflow to estuaries have to be characterized so that the total regime can be understood.

2.4 Tides and Residence Times

In all estuaries, the dilution of seawater by the volume of fresh water inflow is affected by the amount of salt water in the system. The volume of salt water is controlled by two main factors: tides and the volume of the receiving body.

Tides are the rise and fall of the sea around the edge of the land. Tides are driven by the gravity of the Moon and Sun, which causes a bulge in the water on the Earth's surface. Far out at sea, tidal changes go unnoticed, but are very important to the plants and animals that live on the edge of sea, in the "intertidal zone." Tides occur in primarily three different patterns. Diurnal tides are where there is one high and one low tide each day. Semidiurnal tides are where the rise and fall is repeated twice each day. Semidiurnal mixed tides occur where there are unequal tidal heights each day. Tidal levels are different in different parts of the world, but in general the tidal ranges can be small (<1 m) or great (>3 m). Thus, tidal range can be categorized as microtidal, mesotidal, or macrotidal.

The combination of river flow and tides mean there are different types of circulation patterns in estuaries. Salt wedge estuaries are where river flow dominates the mixing and typically freshwater overflows salty water giving rise to strong stratification at a specific point. Well-mixed estuaries are where the wind dominates mixing and there is a strong salinity gradient from the river to the sea, but little to no stratification of the water column. Partially mixed estuaries are where tides dominate the mixing patterns so that there is stratification of salt water on the bottom and fresher water on the top, but this gradient can be variable along the axis of the estuary. Fjord-type estuaries are where sea water is trapped in deep parts of the bay, typically behind a sill, and there is little to no exchange with the surface water.

Because of the mixing of salt and freshwater, water budgets and salt budgets are very important to understanding flow dynamics. In a water budget, the total volume transported out in a unit of time is the sum of the volume transported in by tides plus the volume of the freshwater inflow transported into the estuary from the river. Thus, the residence time (or flushing time) is the volume of the estuary (V_{estuary}) divided by the rate of flow of water leaving the estuary (T_{out}), i.e., Flushing Time = $V_{\mathrm{estuary}}/T_{\mathrm{out}}$. The flushing time is very important because it controls the carrying capacity of wastes, the flushing time for fresh water, the flushing by tidal action, the effects of mixing, and it can be affected by coastal upwelling and downwelling. Thus, flushing rate is the master variable that controls nearly all estuarine processes.

2.5 Estuarine Condition and Water Column Effects

Watershed development such as the construction of dams and withdrawal of water for human use has changed flow regimes, transport of sediments and nutrients, modified habitat, and disrupted migration routes of aquatic species (MEA 2005). These modifications to the hydrologic cycle affect the quantity, quality, and timing of freshwater inflows, and the health of estuaries. Understanding the cascading link between inflow, condition, and response (Fig. 2.1) is the key to understanding how change driven by human and climate systems can drive resistance and resilience of biological communities.

2.5.1 Salinity

The salinity at any point within an estuary reflects the degree to which seawater has been diluted by freshwater inflows. Estuaries are transitional zones between freshwater and marine environments, and as such, display gradients of salinity (0 in freshwater to 35 ppt in seawater) and nutrients (high in freshwater, low in seawater; Montagna et al. 2010). When less dense freshwater flows into more dense saltwater, the freshwater has a tendency to remain primarily on the surface layer (Kjerfve 1979). However, winds and tides tend to mix the water column, creating longitudinal and vertical salinity gradients within estuaries (Day et al. 1989). Estuaries can be classified based on their water balance: (a) positive estuaries have freshwater inputs that exceed evaporation, (b) neutral estuaries have a balance between freshwater input and evaporation, and (c) negative estuaries have evaporation that exceeds freshwater input (Pritchard 1952). Depending on the hydrologic cycle, a system may change seasonally from being a positive to a negative estuary, or vice versa.

Water development projects can reduce the delivery of freshwater to estuaries and also affect the timing of inflow pulses, which can affect organisms adapted to the original salinity conditions. Although estuarine organisms generally have a wide salinity tolerance (euryhaline), most are located only within a portion of

Table 2.1 Selected references for salinity effects on estuarine macrobenthic and epibenthic organisms

Authors	Organism(s) studied	Study location	Salinity tolerance results
Chadwick and Feminella (2001)	Burrowing mayfly *Hexagenia limbata*	USA (Alabama)	Laboratory bioassays showed that *H. limbata* nymphs could survive elevated salinities (LC50 of 6.3 ppt at 18 °C, 2.4 ppt at 28 °C). Similar growth rates at 0, 2, 4, and 8 ppt
Saoud and Davis (2003)	Juvenile brown shrimp *Farfantepenaeus aztecus*	USA (Alabama)	Growth significantly higher at salinities of 8 and 12 ppt than at salinities of 2 and 4 ppt
Tolley et al. (2006)	Oyster reef communities of decapod crustaceans and fish	USA (Florida)	Upper stations (~20 ppt) and stations near high-flow tributaries (6–12 $m^3 s^{-1}$) were typified by decapod *Eurypanopeus depressus* and gobiid fishes. Downstream stations (~30 ppt) and stations near low-flow tributaries (0.2–2 $m^3 s^{-1}$) were typified by decapods *E*
Montagna et al. (2008a)	Southwest Florida mollusk communities	USA (Florida)	*Corbicula fluminea*, *Rangia cuneata*, and *Neritina usnea* only species to occur <1 psu. *Rangia cuneata* good indicator of mesohaline salinity zones with tolerance to 20 psu. Gastropod *N. usnea* common in fresh to brackish salinities. *Polymesoda caroliniana* present between 1-20 psu (oligo- to mesohaline zones). *Tagelusplebius, Crassostrea virginica, Mulinia lateralis, Littoraria irrorata, & Ischadium recurvum* good indicators for polyhaline salinity zones.
Montague and Ley (1993)	Submersed vegetation and benthic animals	USA (Florida)	Mean salinity ranged from ~11 to 31 ppt. Standard deviation of salinity was best environmental correlate of mean plant biomass and benthic animal diversity. Less biota at stations with greater fluctuations in salinity. For every 3 ppt increase in standard
Rozas et al. (2005)	Estuarine macrobenthic community	USA (Louisiana)	Increased density and biomass with increases in freshwater inflow and reduced salinities. Salinity ranged from 1 to 13 psu
Finney (1979)	Harpacticoid copepods *Tigriopus japonicus*, *Tachidius brevicornis*, *Tisbe sp.*	USA (Maryland)	All species tested for response to salinities from 0 to 210 ppt. *Tigriopus* became dormant at 90 ppt died at 150 ppt. *Tachidius* became dormant at 60 ppt, died at 150 ppt. *Tisbe* died shortly after exposure to 45 ppt

(continued)

Table 2.1 (continued)

Authors	Organism(s) studied	Study location	Salinity tolerance results
Kalke and Montagna (1991)	Estuarine macrobenthic community	USA (Texas)	Chironomid larvae and polychaete *Hobsonia florida*: increased densities after freshwater inflow event (1–5 ppt). Mollusks *Mulinia lateralis and Macoma mitchelli:* increased densities and abundance during low flow event (~20 ppt). *Streblospio benedicti* and *Medioma*
Keiser and Aldrich (1973)	Postlarval brown shrimp *Penaeus aztecus*	USA (Texas)	Shrimp selected for salinities between 5 and 20 ppt
Montagna et al. (2002b)	Estuarine macrobenthic community	USA (Texas)	Macrofauna increased abundances, biomass and diversity with increased inflow; decreased during hypersaline conditions. Macrofaunal biomass and diversity had nonlinear bell-shaped relationship with salinity: maximum biomass at ~19 ppt
Zein-Eldin (1963)	Postlarval brown shrimp *Penaeus aztecus*	USA (Texas)	In laboratory experiments with temperatures 24.5–26.0 °C, postlarvae grew equally well in salinities of 2–40 ppt
Zein-Eldin and Aldrich (1965)	Postlarval brown shrimp *Penaeus aztecus*	USA (Texas)	In laboratory experiments with temperatures <15 °C, postlarval survival decreased in salinities <5 ppt
Allan et al. (2006)	Caridean shrimp *Palaemon peringueyi*	South Africa	At constant salinity of 35 ppt, respiration rate increased with increased temperature. At constant temperature of 15 °C, respiration rate increased with increased salinity
Ferraris et al. (1994)	Snapping shrimp *Alpheus viridari*, Polychaete *Terebellides parva*, sipunculan *Golfingia cylindrata*	Belize	Organisms subjected to acute, repeated exposure to 25, 35, or 45 ppt. *Alpheus viridari* hyperosmotic conformer at decreased salinity, but osmoconformer at increased saliniry. *Golfingia cylindrata* always osmoconformer. *Terebellides parva* always osmoconformer; decreased survival
Lercari et al. (2002)	Sandy beach macrobenthic community	Uruguay	Abundance, biomass, species richness, diversity, and evenness significantly increased from salinity of ~6 ppt to salinity of ~25 ppt
Chollett and Bone (2007)	Estuarine macrobenthic community	Venezuela	Immediately after heavy rainfall (~25 psu), spionid polychaetes showed large increases in density and richness versus normal values (~41 psu)

(continued)

Table 2.1 (continued)

Authors	Organism(s) studied	Study location	Salinity tolerance results
Dahms (1990)	Harpacticoid copepod *Paramphiascella fulvofasciata*	Germany (Helgoland)	After 2 h, no mortality in salinities of 25–55 ppt. Almost all displayed dormant behavior <20 and >55 ppt
McLeod and Wing (2008)	Bivalves *Austrovenus stutchburyi* and *Paphies australis*	New Zealand	Sustained exposure (>30 d) to salinity <10 ppt significantly decreased survivorship
Rutger and Wing (2006)	Esturaine macroinfaunal community	New Zealandz	Infaunal community in low salinity regions (2–4 ppt) showed low species richness and abundance of bivalves, decapods, and Orbiniid polychaetes, but high abundance of amphipods and Nereid polychaetes compared to higher salinity regions (12–32 ppt)
Drake et al. (2002)	Estuarine macrobenthic community	Spain	Species richness, abundance, and biomass decreased in the upstream direction, positively correlated with salinity. Highly significant spatial variation in macrofaunal communities along the salinity gradient. Salinity range: 0–40 ppt
Normant and Lamprecht (2006)	Benthic amphipod *Gammarus oceanicus*	Baltic Sea	Low salinity basin (5–7 psu). Physiological performance examined from 5 to 30 psu. Feeding and metabolic rates decreased with increasing salinity; nutritive absorption increased. Feces production and ammonia excretion rates decreased strongly from lowest to highest salinity. Greatest scope for growth at 7 psu.

their salinity range. Thus, salinity gradients play a major role in determining the distribution of estuarine organisms (Table 2.1). Secondary production by estuarine benthic macrofauna in particular is known to increase with increases in freshwater inflow (Montagna and Kalke 1992). Salinity gradients also can act as barriers to predators and disease. Two important oyster predators in Gulf of Mexico estuaries, the southern oyster drill *Thais haemastoma* and the stone crab *Menippe mercenaria* are intolerant of sustained salinities below 15 psu (Menzel et al. 1958; MacKenzie 1977). Freshwater inflow, depending on the volume, can dilute or even eliminate infective *Perkinsus marinus* oyster disease particles in low salinity areas (Mackin 1956; La Peyre et al. 2009). The timing of freshwater inflows is also important to estuarine organism abundance and distribution because the organisms have evolved over long periods to particular regimes of freshwater inflow and associated hydrologic conditions (Montagna et al. 2002).

2.5.2 Sediments

In addition to changing salinity levels, freshwater inflow provides nutrients, sediments, and organic materials that are important for overall productivity of the estuary. Thus, any upstream changes in inflow will affect the amount and timing of their delivery to the estuary as well (Alber 2002). High estuarine turbidity is generally observed during high-flow periods due to elevated sediment inputs. Sediments are delivered to estuaries from rivers and streams by freshwater inflow, which helps to build and stabilize wetlands, tidal flats, and shoals (Olsen et al. 2007). Particulate matter carried by rivers also provides the primary energy source for organisms living in the estuarine environment (Day et al. 1989).

Freshwater diversion from estuaries is decreasing the delivery of water and sediment to the coastal zone. Within the continental US, approximately 90 % of the sediment being eroded from land is stored somewhere between the river and the sea (Meade et al. 1990). Changes in sediment discharge over the past 200 years are primarily due to anthropogenic factors including (a) deforestation and agriculture, (b) changes in land management strategy, and (c) construction of dams, diversions and levees (McKee and Baskaran 1999). Worldwide, reservoirs and water diversions have resulted in a net reduction of sediment delivery to estuaries by roughly 10 %, and prevent about 30 % of sediments from reaching the oceans (Syvitski et al. 2005; Vörösmarty et al. 2003).

2.5.3 Nutrients

The nutrient content of freshwater flows entering estuarine waters is important because it is closely linked to primary production (Valiela 1995). In estuarine systems, nitrogen is the principal limiting element, followed by phosphorus.

The addition of nutrients to estuaries is a natural process that has been greatly enhanced by human activities. In recent decades, population growth, agricultural practices, wastewater treatment plants, urban runoff, and the burning of fossil fuels have greatly increased nutrient inputs over the levels that occur naturally (Bricker et al. 1999). The concentrations of nutrients in estuaries are dynamic in space and time as a function of inputs and outputs from river flows and oceanic exchange as well as biological uptake and regeneration (Day et al. 1989). Salinity is generally an inverse indicator of the availability of land-derived nutrients, with low salinities (high freshwater inflow) linked to high nutrient concentrations (Pollack et al. 2009; Montagna et al. 2010).

Freshwater inflow can enrich estuarine nutrients and increase primary and secondary production (Livingston et al. 1997; Brock 2001). Conversely, decreased inflow has been linked to decreased rates of both primary and secondary production (Drinkwater and Frank 1994). Excess loading of nutrients to coastal waters can cause dense, long-lived algal blooms that block sunlight to submerged aquatic vegetation. The decay of these blooms consumes oxygen that was once available to fish and shellfish, which can result in anoxic or hypoxic conditions (Rabalais and Nixon 2002). Excess nutrients can thus cause degraded water quality and affect the use of estuarine resources such as fishing, swimming, and boating (Bricker et al. 1999).

2.5.4 Biological Indicators

Change in freshwater inflow to an estuary not only changes the salinity of an estuary, but also nutrient concentrations. Increases in freshwater inflow usually lead to an increase in bioavailable nutrients, which in turn stimulate primary production. This primary production is often in the form of phytoplankton growth. The phytoplankton growth in turn stimulates secondary production by organisms such as zooplankton and benthic suspension feeders. Following the increase in secondary production, there is often an increase in tertiary production by organisms such as shrimps and fishes. This process is an oversimplification of the biological response to an increase in freshwater inflows. Every estuary and coastal zone is different and complex food webs exist rather than simple food chains. Because it is impossible to determine the exact changes in every population as they respond to changes in freshwater inflow, we instead approximate biological effects using biological indicators.

Biological indicators are individual species or communities of species that integrate changes in the environment so that when monitored, can indicate changes or stability in a particular environment. We expect indicator organisms to do for us today what canaries did for coal miners in the eighteenth and nineteenth centuries. Indicator organisms should have at least five characteristics that make them useful in applied research (Soule 1988). (1) They should direct our attention to qualities of the environment. (2) They should give us a sign that some characteristic is present. (3) They should express a generalization about the environment. (4) They should suggest a cause, outcome or remedy. (5) Finally, they should show a need for action.

Benthic invertebrate communities have been widely used as indicators of ecological health in environmental assessment, pollution detection, and ecological monitoring studies. The benthic community is unique among coastal and marine organisms for several reasons. First, they are predominantly permanent residents of estuaries, unlike much of the more visible nekton that are made up of large populations of migratory organisms. Second, they are relatively long-lived compared to plankton. Third, the benthos are relatively immobile and fixed in space, unlike nekton and plankton that move freely or with currents. In addition, everything dies and ends up in the detrital food chain, which is utilized by the benthos. Because of gravity, there is a record of all environmental change in the sediments, and benthos are commonly referred to as the "memory" of the ecosystem because this record of past events is layered in the sediments. This combination of characteristics means that the benthic community integrates change in ecosystems over long time scales. Benthos are therefore the best sentinel group responding to changes in external conditions without the complication of movement to different regions of the coastal zone. Because benthic organisms are relatively immobile, they are usually the first organisms affected by environmental stress. Many ecological monitoring programs use benthic abundance, biomass, and diversity as ecological indicators of the state, productivity, or health with respect to changes in the environment.

Diverse and abundant populations of benthic invertebrates provide a necessary food source for many aquatic and terrestrial species. Because of the importance of benthic organisms in the estuarine food chain, fluctuations in their abundance can influence recruitment patterns in coastal fisheries and avian migratory behavior. Therefore, it is important to continuously monitor the abundance and diversity of benthic infauna within an estuarine system.

There are good ecological conceptual models that provide a scientific basis for interpreting the data generated in benthic monitoring and detection studies. These approaches utilize many single species, community studies, and statistical models. One of the most important concepts is the succession model proposed by Rhoads et al. (1978). They applied scientific theories of ecological succession and its relation to productivity to suggest ways that dredge-spoil could be managed to enhance productivity. The same year, Pearson and Rosenberg (1978) published a review showing how benthic community succession changed in relation to organic enrichment. The central tenant of this theory is that distance from a pollution source is analogous to time since a natural disturbance. Thus, the sequence of colonization and succession events that occur after a disturbance are similar to the changes in communities observed with distance from a pollution source. There is typically a gradient from smaller, less diverse, pioneering species limited to surface sediments to larger, more diverse, climax assemblages of deeper dwelling organisms. The gradient changes over both distance from a pollution source or is represented by community development over time after a disturbance. Thus, we have a scientific justification for benthic community structure and biodiversity studies as an assessment tool. Since these two classic studies, numerous other studies have demonstrated the value of benthic communities as an excellent indicator of environmental health.

Ecological health can be defined by benthic metrics employing the following series of linked definitions: The condition of integrity is assessed when community structure and diversity are stable over long periods of time. The condition of function is assessed when biomass (the best indicator of productivity) is stable over long time periods. These three metrics: abundance, biomass, and species diversity are easily obtainable in routine sampling programs.

An important objective of many resource agencies is to quantify the relationship between bioindicators of marine resource populations and freshwater inflows to bays and estuaries. However, there is year-to-year variability in population densities and successional events in estuarine communities. This year-to-year variability is apparently driven by long-term, and global-scale climatic events. For example, El Niño affects rates of precipitation and concomitantly rates of freshwater inflow along the Texas coast, which in turn influences salinity patterns in Texas bays (Tolan 2007). Therefore, the best approach is to document long-term changes in populations and communities that are influenced by freshwater inflow. The best indicator of productivity is the change in biomass of the community over time (Banse and Moser 1980). Based on initial sampling of 1–4 years of benthic data in Texas bays, it was originally concluded that inflow does increase benthic productivity (Kalke and Montagna 1991; Montagna and Kalke 1992, 1995). However, further analysis of the data set over a 5-year period demonstrated that the largest effect may not be on productivity, but may be on community structure (Montagna and Li 2010). This implies that reduced inflows may not only reduce productivity (a measure of ecosystem function), but may also change the composition of species in an estuary (a measure of ecosystem structure).

Texas Coastal Bend estuaries were studied over a 20-year period by Montagna (2008) to determine the long-term response of benthic organisms to freshwater inflow. Results show that the biological effects on benthic communities appear to be driven by the El Niño cycle. Flood conditions introduce nutrient rich waters into the estuary that result in lower salinity. During El Niño periods, the lowest salinities and highest nutrient values were recorded. During these periods, the spatial extent of the freshwater fauna is increased, and the estuarine fauna replaced the marine fauna in the lower end of the estuary. The high level of nutrients stimulated a burst of benthic productivity (of predominantly freshwater and estuarine organisms), which lasted about 6 months. This was followed by a transition to a drought period with low inflow resulting in higher salinities, lower nutrients, dominance by marine fauna, decreased productivity, and decreased abundances.

Florida Bay was examined to determine the relationship between commercially important pink shrimp (*Farfantepenaeus duorarum*) recruitment and freshwater inflow characteristics (Browder et al. 2002). Experiments were conducted to determine the rates of juvenile shrimp growth and survival at varying temperatures and salinities and the results were used to refine an existing model of potential pink shrimp recruitment. Results showed high survival over a wide salinity range except at extreme temperatures. In particular, shrimp were least tolerant of high salinity at low temperatures and low salinity at high temperatures. Maintenance of freshwater inflow was important to provide favorable salinities over the greatest amount of suitable and accessible habitat. Timing of flows in relation to arrival of postlarvae from offshore spawning grounds was also found to be important (Browder et al. 2002).