II. OVERVIEW OF THE ECOSYSTEM

An estuary is a semi-enclosed body of water with salinity intermediate between salt and fresh water. The Galveston Bay system is set apart from the Gulf of Mexico by a barrier island and two peninsulas. Freshwater flowing from the landmass is detained by these barriers, which are pierced by three inlets: the large, man-modified Bolivar Roads; the small, natural San Luis Pass; and the smallest, man-made Rollover Pass (see Figure 1). The brackish water ecosystem within the bay is maintained by the solar-powered hydrologic cycle. Sunlight, warming the surface of the Gulf of Mexico, evaporates gaseous water vapor which rises into the atmosphere and is carried over the landmass by prevailing southerly winds. This represents the uphill portion of the hydrologic cycle. Cooling over the continent, the moisture condenses and falls to earth as precipitation, initiating the downhill component of the cycle. A portion of the rainfall evaporates or moves upward through green plants as evapotranspiration, returning to the atmosphere. Another portion sinks into the soil, eventually to emerge as groundwater, slowly advancing toward the gulf. The remainder flows across the surface of the earth coalescing into rivulets, brooks, streams and rivers. Enroute, both surface runoff and groundwater acquire a number of chemicals in solution. This freshwater inflow transports dissolved and suspended materials to the estuary.

Texas history has been shaped by rivers that provided water, transportation, and a means of waste disposal. Although the total surface of the rivers and streams is small compared to the land mass and the Gulf of Mexico, rivers are among the natural ecosystems most intensely used by man. The role of rivers and streams has changed drastically over the last century. When Europeans first colonized the North American continent, rivers were the arteries of the emerging nation, used for exploration and commercial transport, and they dictated settlement patterns. Today rivers and their riparian wetlands function as kidneys, processing and purifying the wastes of an industrialized nation (Meyer, 1990). A river is sometimes likened to the veins of a leaf, branching out from its stem and midrib to smaller and smaller tributaries. But rivers flow in the reverse direction and, more appropriately, should be considered as the entire leaf, bounded by the dimensions of the watershed, exporting a portion of the organic production of the watershed via tributaries of ever-increasing dimension to downstream habitats.

The character of streams and rivers changes from source to mouth in a predictable fashion, in what is termed the river continuum (Vannote et al., 1980). Stream size and water volume increase, and both the kind of plants and animals and the overall number of species change as well. **Upland ecosystems** contribute surface runoff and groundwater inflow (springs and seeps) to **stream-riparian ecosystems**, often filtered by greenbelts of riparian corridor vegetation. The upper tributaries may be shaded, with very few, if any, rooted plants and algae growing in the waters. The organisms using these streams depend on decomposing organic matter and terrestrial animals imported from adjacent terrestrial habitats for their sustenance. As the streams increase in width they are less shaded and sufficient sunlight penetrates the water to support aquatic plants. In the middle reaches the organic matter produced within the stream may exceed that which is imported, the stream is self-sustaining (autotrophic) in that the organic matter produced by photosynthesis exceeds that consumed by respiration, and species diversity peaks. In the downstream reaches the current is reduced and accumulated suspended sediment decreases light penetration and aquatic photosynthesis. The stream once again becomes dependent on imported organic materials (heterotrophic).

River-floodplain ecosystems contribute water, nutrients and sediments to floodplain forests, which return organic material of terrestrial origin to the river system (Figure 2). The **estuary ecosystem** is closely coupled, with two-way interchange, to the river-floodplain and nearshore gulf ecosystems. The **nearshore gulf ecosystem** is a primary contributor of organisms, as larvae and juveniles of many marine species enter the estuary seeking food and sheltering habitat. A few of the marine species feed in the lower reaches of the river-floodplain ecosystem.

The aquatic ecosystems of the watershed (Figure 2) provide both "goods" and "services" to society. Ecosystem "goods" include food, such as freshwater finfish and estuarine finfish and shellfish. Ecosystem "services" include maintaining the hydrologic cycle, regulating climate, cleansing water and air, maintaining the gaseous composition of the atmosphere, storing and cycling essential nutrients, absorbing and detoxifying pollutants, and providing sites for recreation, tourism, research and inspiration. When societal activities disrupt the essential functions of ecosystems, the assimilative capacity of natural systems is exceeded, and the normal flow of "goods" and "services" provided by healthy ecosystems is impaired. Highly managed ecosystems, such as agroecosystems and urban-industrial ecosystems, are embedded within, and highly dependent upon, unmanaged natural ecosystems which provide our life-support (Odum 1989).

There are no major natural lakes in the watershed but 37 major reservoirs have been constructed, 25 in the upper Trinity River basin alone (Stanley, 1989). Ecologically, this presents a major change when a fast-moving water (lotic) ecosystem encounters a slow-moving water (lentic) ecosystem. As the narrowly channeled river flow enters the broad reservoir, water velocity is greatly reduced and suspended sediments (with attached pollutants) sink to the bottom. With greater water clarity and less downstream transport, plankton shifts from being a minor river component to a major lake component and the food web becomes autotrophic. Species diversity of both plants and animals increases and exotic species, introduced to enhance recreational fishing, become important. The natural flooding regime is altered below the dam and upstream migration is blocked.

Estuaries are among the most naturally fertile waters in the world. This results from their unique juxtaposition at the edge of the continent. Estuaries play a special ecological role because they receive nutrients from four sources: (1) freshwater flowing off the land, (2) tidal exchange with the ocean (Gulf of Mexico in this instance), (3) the atmosphere, and (4) the recycling of material from the estuarine bottom sediments.

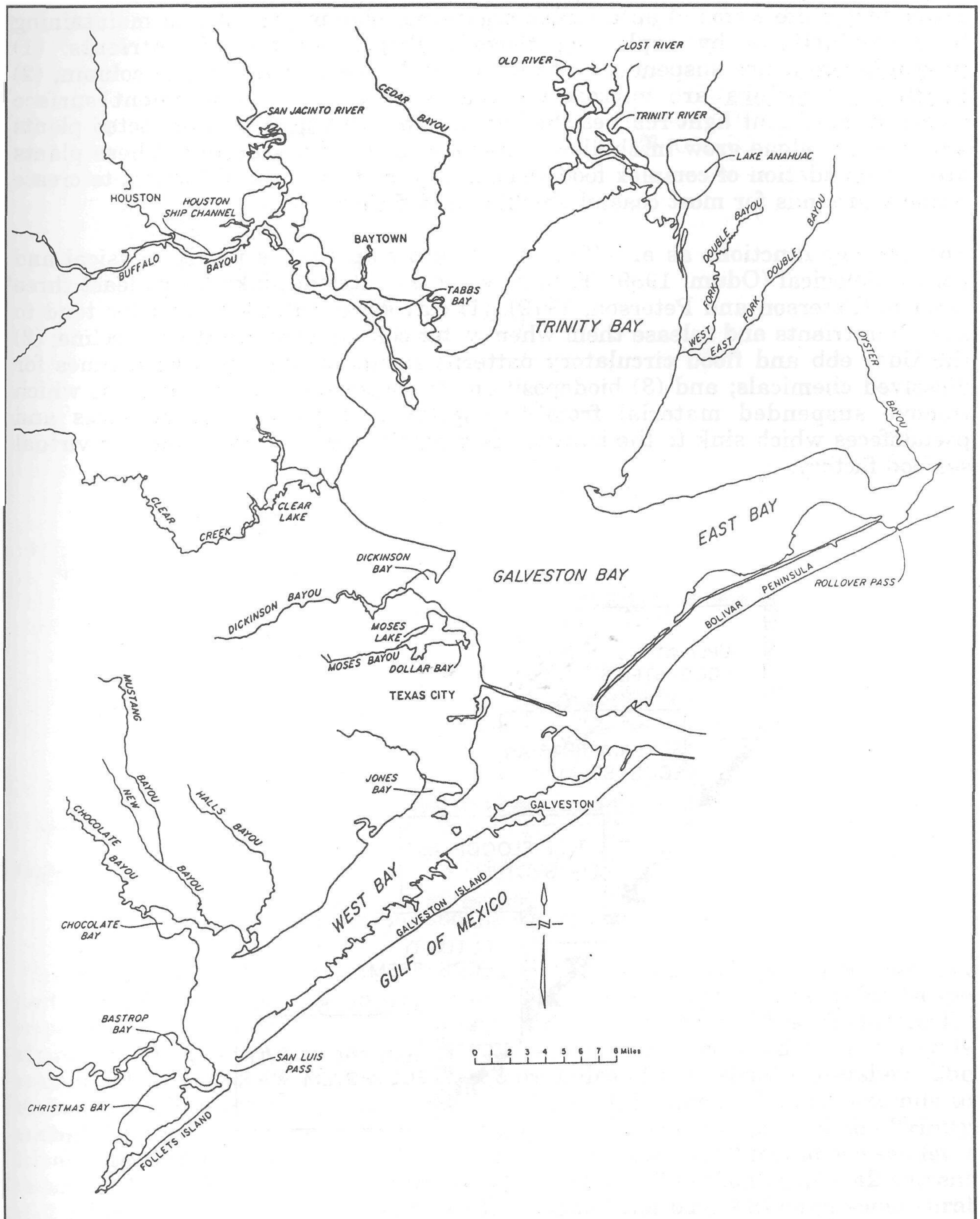


Figure 1. Map of Galveston Bay

Three major life forms of autotrophic organisms play major roles in maintaining high productivity by exploiting these multiple sources of nutrients: (1) phytoplankton are suspended within the sunlit zone of the water column, (2) benthic microflora are microscopic plants living on the sediment surface wherever sufficient light reaches the bottom, and (3) macroflora or rooted plants and rootless algae grow in shallow water and along the shoreline. These plants are the foundation of complex food webs and provide structural habitat to create nursery grounds for most coastal shellfish and finfish.

The estuary functions as an efficient nutrient trap that is partly physical and partly biological (Odum, 1989). Estuaries act as nutrient sinks for at least three reasons (Peterson and Peterson, 1979): (1) clay-sized sediment particles tend to adsorb nutrients and release them when water column concentrations decline; (2) the tidal ebb and flood circulatory patterns result in long residence times for dissolved chemicals; and (3) biodeposition by suspension-feeding animals which remove suspended material from the water and package it as feces and pseudofeces which sink to the bottom. As a result, the estuary becomes a virtual seafood factory.

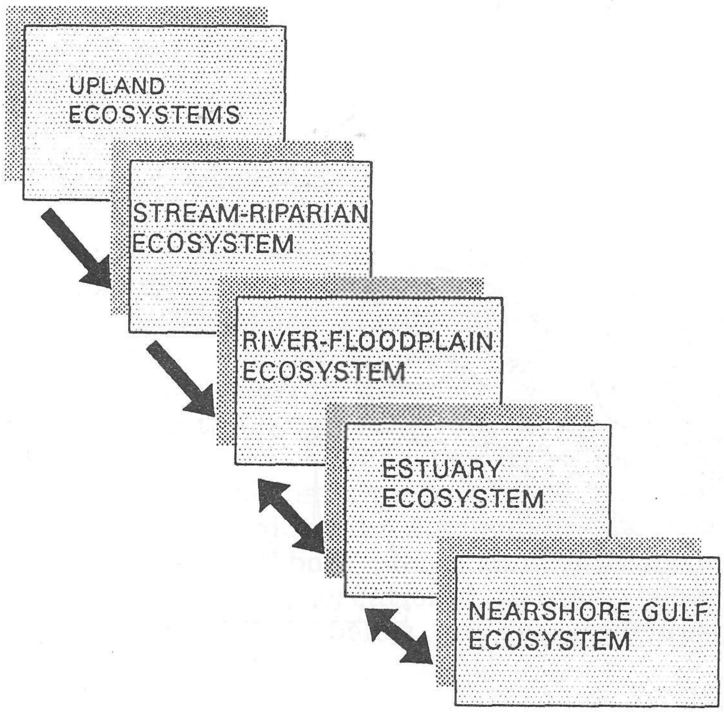


Figure 2. Watershed connections, showing unidirectional flow from upland to stream-riparian to river-floodplain ecosystems and bidirectional interchange between the river-floodplain, estuary, and nearshore Gulf ecosystems.

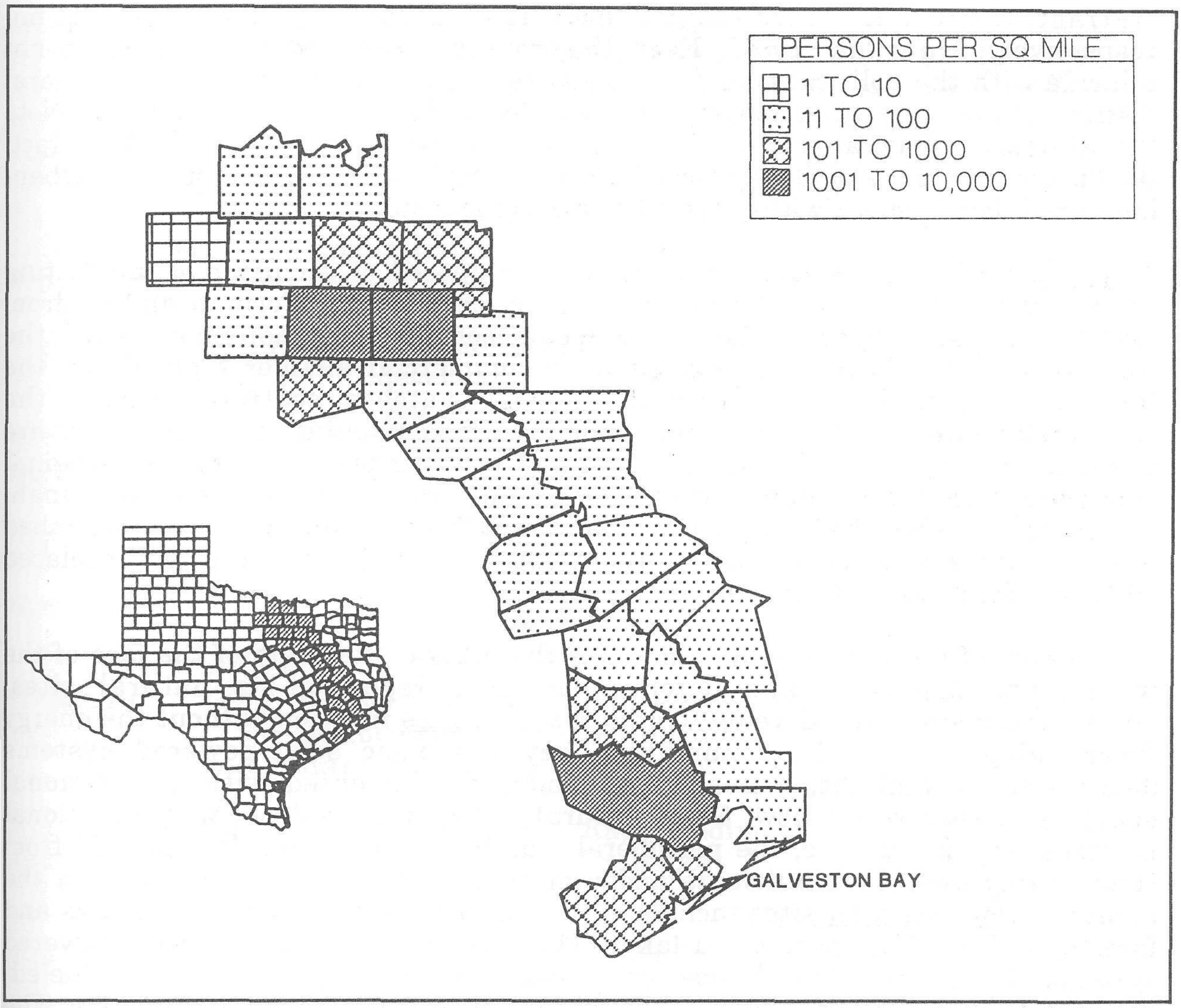


Figure 3. Population density of the Galveston Bay watershed.

A Landscape Approach

The realization that an estuary is affected by and reflects ecological processes and perturbations that occur far upstream in its watershed suggests that a landscape approach would be useful to understanding the system. This dramatically changes the scope of the issue. The 600 square miles covered by the bay is equivalent to only 2.4% of the 25,256 square miles of terrestrial watershed. The drainage basin stretches northward 400 miles and, in Cooke County, extends to within 6 miles of the Red River and Oklahoma. The sinuous path of the Trinity River extends for 715 miles from Trinity Bay to its source 1250 feet above sea level (Stanley, 1989). This large watershed is inhabited by 7.7 million people; 42 percent (3.2 million) live in the four counties which bound the bay. Although some rural counties (Jack, Leon, Trinity, Freestone, and Montague) have fewer than 20 persons per square mile, the urban centers can reach 2000 persons/sq. mi

(Tarrant, Harris and Dallas counties have 1348, 1625, and 2105 persons/sq. mi, respectively; Kingston, 1991). Even though the watershed boundaries do not coincide with the political boundaries used to aggregate census data, the general distribution of population density for the watershed is indicated in Figure 3. Note that Galveston Bay, at the lower extremity, is dwarfed by its watershed. In fact, the 600 square miles of Galveston Bay are matched by 580 square miles of urban-industrial development within the city limits of Houston.

A landscape is a heterogeneous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout (Forman and Godron, 1986). For our purposes, the landscape is considered synonymous with the watershed. Viewed from the window of a commercial airliner high above, the landscape resembles a mosaic of differing patches scattered across the countryside. All landscapes share a common fundamental structure; they are composed entirely of patches, corridors, and a background matrix. The original matrix for the upper watershed was blackland prairie and post oak savannah. The middle reaches drained pine and hardwood forest, while the lower watershed was comprised of coastal prairies. Today much of the matrix has been replaced with crop lands and exotic grasses.

The impact of development by humans is the drastic alteration of the face of the watershed. The landscape patches can be categorized as natural sites, domesticated sites, and developed sites. Natural sites function without the energy flows being controlled by humans. They are basic solar-powered systems dependent on sunlight, rainfall and winds, supplemented with gravitational energy to power water flow. Some natural sites are subsidized with additional insetenergy; for example, the peripheral marshes of Galveston Bay benefit from tidal energy delivering nutrients and removing waste products to and from the habitats. Domesticated sites include agricultural lands, managed woodlands and forests, and artificial ponds and lakes. These sites are subsidized solar-powered systems that benefit from human-controlled work energy, such as fossil-fueled-powered farm machinery, human and animal labor, imported fertilizers, etc. The amount of energy consumed per unit area per year (energy density) may reach twice that of natural sites (Odum, 1989). The amount of air, water and soil pollutants released at these sites is also increased. Developed sites are the urban and industrial sites fabricated by humans. These are fuel-powered systems and the amount of energy consumed per unit area each year may be 10 times that typical of natural sites. Concomitantly, the volume of pollutants produced is similarly increased. Developed sites are also parasitic in that they are maintained only by importing large quantities of fuel and materials from outside of their boundaries. Odum (1989) has used the term "ghost acreage" to describe the unbounded area beyond the site which is required to sustain the population within the site. A hypothetical comparison of the characteristics for three potentially contiguous landscape patches is presented in Table 1.

Landscapes exhibit three characteristics - structure, function, and change (Forman and Godron, 1986). Structure results from the spatial relationships among the distinctive ecosystems present. Function arises from interactions among the spatial elements; for example, the flow of energy, materials, and species among the component ecosystems. Change results from alteration in the structure and function of components of the ecological mosaic over time. Human activity has greatly accelerated the rate of change. It is useful to consider the landscape as a hierarchy, a graded series of compartments. Each level in a hierarchy influences what goes on in adjacent levels. Processes found at lower levels are frequently constrained in some way by other processes at higher levels. The different levels of organization have different, and often unique, features. Since they are all linked together, events that happen at one level may affect subsequent events at another level (Odum, 1989).

Table 1. A comparison of ecosystem components typical of native, cultivated and developed landscape patches.

ECOSYSTEM COMPONENT	NATIVE SITE	CULTIVATED SITE	DEVELOPED SITE
Site	Prairie	Corn Field	Shopping Center
Surface	Native Grasses	Row Crop	Building, Parking Lot
Fertilizer	Nitrogen-fixing Microbes, Recycled Manure	Imported Nitrogen, Phosphorus	Processed Sewage
Soil Erosion	Slow Percolation, Water Storage	Rapid Sediment Transport	Rapid Runoff, Pollutants (motor oil,)
Flora	Native High Diversity	Exotic Low Diversity	None
Fauna	Native Resident (meadowlark)	Native Transitory (blackbirds)	Exotic (house sparrow, house mouse, cockroaches)
Corridor	Hedgerow, Riparian Vegetation	Fenceline	Highway

An important consequence of hierarchical organization is that as components, or subsets of components, are combined to produce larger functional wholes, new properties emerge that were not present or not evident at the level below. The emergent property principle defines an emergent property as one that results from the functional interaction of the component parts. Therefore an emergent property cannot be predicted by studying components that are isolated or decoupled from the whole unit.

The scale and pace of events also changes in traversing the landscape. For example, the flow of extreme headwaters is likely to be intermittent, following precipitation events. Further downstream, at lower elevation, sufficient groundwater may enter the brook to provide permanent flow. Thus surface water flow is rapid and pulsed, while groundwater flow is delayed (by days, weeks or months) but prolonged. A single tree can shade the brook from bank to bank and aquatic vegetation may be absent or very limited. As numerous brooks coalesce to create a stream, the width, depth and volume of water increase. Fallen trees provide obstacles, and sediments and leaf detritus gather where currents diminish. Decomposition of organic matter accelerates where microbes and invertebrates find sheltered water. Where adequate light exists, plants take root in softer sediments and dissolved oxygen levels increase. When stream width increases and the overhead tree canopy diminishes, beds of aquatic plants develop. These provide food and shelter for additional fishes and invertebrates, thus biotic diversity increases. As sediment loads accumulate, clear brooks become murky streams and muddy rivers. Plants disappear and photosynthesis declines. Chemical and biological oxygen demand increase and oxygen levels decline. Visual-feeding fishes and invertebrates give way to olfactory-feeders (catfishes) and detritivores (suckers).

A human observer standing on the shore of Galveston Bay typically recognizes entities at two ends of a spectrum - individuals and landscapes. The **individuals** are the actual species seen -the fish reeled in from the waters below, the crab scurrying across the beach, the bird flying overhead. The **landscape** is the surrounding environs - the water, the beach, the nearby marsh and surrounding uplands. Unseen are the intervening hierarchical entities (Figure 4). Individuals have life histories in that they are born in particular places, grow up in certain (perhaps other) habitats, and reproduce to ensure continuity of the species. The aggregate of individuals form a **population** which may migrate to and from the bay. Populations can go extinct. Usually it is difficult to envision a population because there are many individuals, frequently too many to count, spread over a large area, often out of sight. Populations of individuals exhibit birth rates, death rates, and changes in gene frequency, resulting in evolutionary trends.

When populations of different plants and animals intermingle they create a **community**, may compete for scarce resources, establish a food web as they eat and are eaten, and thus exhibit diversity, competition, and predation as community characteristics. Subaerial and intertidal communities, like marshes, are visible and commonly recognized. Submerged communities, like muddy or sandy bottoms and deep oyster reefs, are out of sight and less well known. Communities of plants or shell add structural complexity to the environment while moderating the effect of external forces, such as waves, currents, and predation, on community inhabitants.

Both physical (abiotic) and biological components demonstrate emerging properties in ascending the hierarchy. When the non-living components of the environment are added to communities to create **ecosystems**, new functions like energy flow and the cycling of nutrients arise and can be measured. But ecosystems are difficult to see clearly because they have fuzzy edges and come in

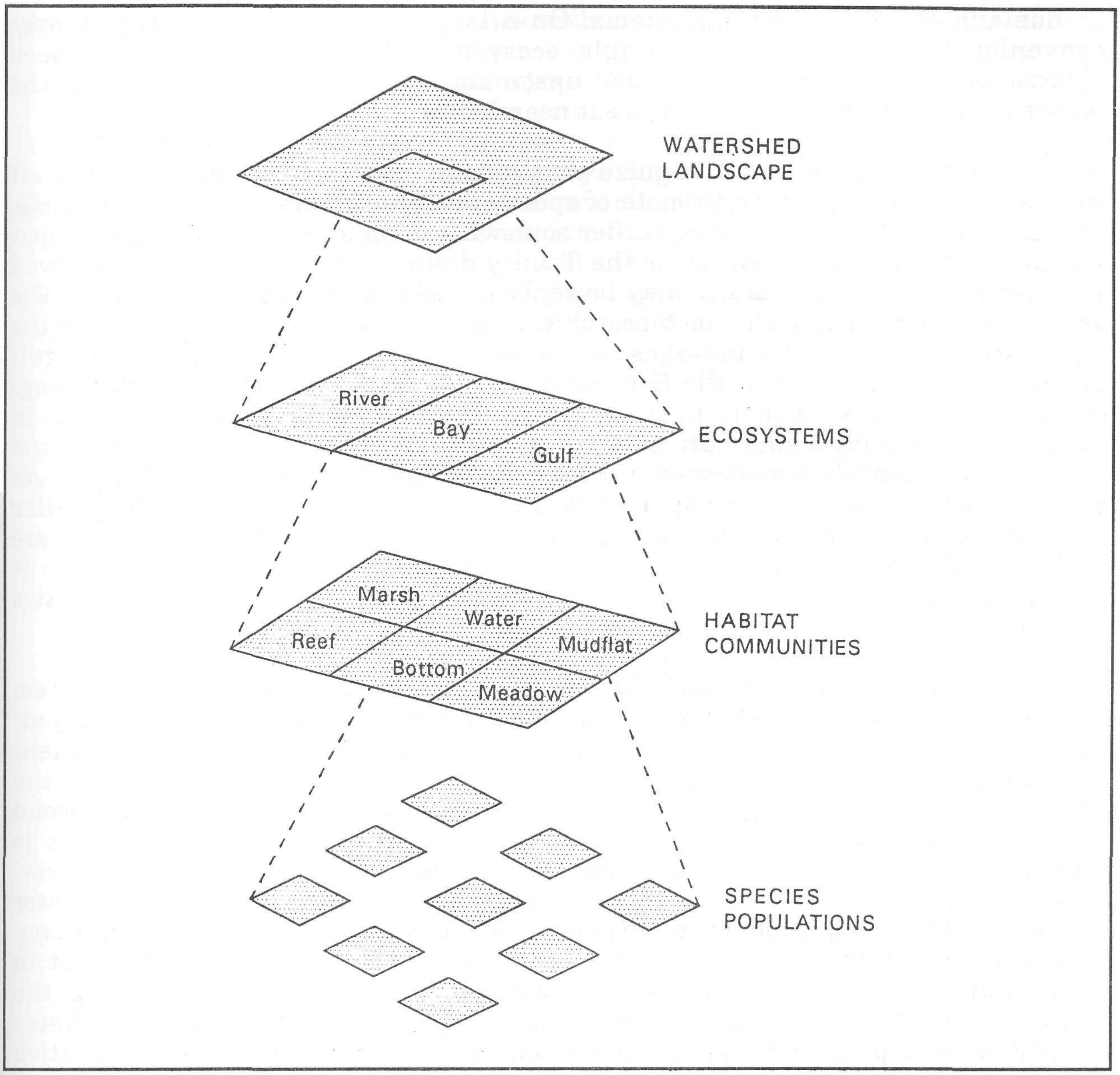


Figure 4. The hierarchical organization of natural systems. The watershed, surrounded by other contiguous watersheds, near the bay is comprised of river, bay and gulf ecosystems. The bay ecosystem is occupied by various types of matrix and patch habitat communities. Each community is created and occupied by populations of various commingling species. Ecosystem characteristics will limit the types of habitats which may occur, while the physical characteristics of each habitat will influence the type of species that occupy the habitat.

all sizes. From the perspective of bacteria and parasites, individual fishes, oysters or humans are wonderful ecosystems. On a larger scale, Galveston Bay can be conveniently considered as a single ecosystem. But the bay is influenced significantly by other ecosystems, upstream and downstream, within the **watershed landscape** and the adjacent nearshore gulf.

Some observers intuitively recognize that spatial and temporal variation affect their view of the bay. The aggregate of species seen in the lower bay (for example, the bay side of Galveston Island) differ somewhat from species frequenting upper bay shorelines (such as Kemah or the Trinity delta). Species commonly observed at one site during the summer may be replaced with other species in winter. The spatial and temporal scales of hierarchical levels are also flexible, even for the same species at different stages of its life cycle. For example, adult gulf menhaden range widely in the Gulf as members of the nekton (free-swimming) community but move inshore to spawn. Their eggs have a brief (48 hr) sojourn in the surface microlayer and hatching larvae continue as members of the plankton community, passively transported into the bay nursery. Larval menhaden prey on zooplankton. Juveniles develop basket-like gillrakers to capture the smaller phytoplankton and prosper as nekton, but lower on the food chain. Before they are one year old, juveniles migrate back to the Gulf to mature and reproduce. This is an example of a single species spending different life stages in different localities as a member of quite distinct communities.

Two other ecosystem characteristics are of interest. Frequently one ecosystem component affects a second component, that in turn affects the first component. Such feedback loops underlie many ecological processes. If the first component stimulates the second component, but the second component then inhibits the first, it is termed negative feedback. If the first component stimulates the second component, which in turn stimulates the first component even further, it is termed positive feedback. For example, under favorable conditions oysters grow rapidly and create more reef surface (oyster shell) which permits more oyster larvae to settle and produce additional reef, a positive feedback mechanism. However, an abundance of oysters may encourage more oystermen to invest in additional boats, which remove more oysters and their shells, reducing the available substrate for oyster larvae, and eventually shrinking the oyster population to a point where it is uneconomical to harvest them; this is negative feedback.

Next, wherever two different components of the landscape come in contact an edge is created. The edge may exist between a patch and the matrix or between two patches. The edge may be sharp and distinct, as where land meets the water, or diffuse, as found at a tidal marsh, where the water's edge advances and retreats with each tide, creating a gradient known as an ecotone. Certain species which require two distinct habitats to meet their life requirements may exist only along edges; others specialize in ecotones. Both are known as edge species. Biologically, edges are where the action is. The nearshore gulf is more productive than the offshore gulf because the edge of the continent provides nutrients and habitat unavailable offshore. Embayments are indentations in the continent, increasing the length of shoreline. Marshes with a reticulated pattern of tidal creeks and blind bayous have more shoreline for a given area and are more beneficial to the estuary than marshes with a straight margin along the bayshore.

Journey To The Sea

It is apparent the effect of the processes occurring within the watershed may extend hundreds of miles to the estuary. Some of these processes are vital. Without freshwater inflow, and the nutrients and sediments transported therewith, the estuary would not exist; it would be a lagoon, a salty extension of the gulf. Rivers do not discriminate. If a material reaches the river, it will be transported, perhaps undergoing transformation enroute. Figure 5 portrays the determinants of water quality in sequential order. Precipitation results in surface runoff and groundwater inflow to initiate the stream. Dissolved and suspended materials are incorporated into the flow from the moment, or even before, raindrops contact the earth. Point and nonpoint source discharges add various contaminants to the flow, particularly from urban-industrial and intensely cultivated sub-watersheds. Stream microorganisms are able to consume or reduce contaminant levels within the waterway. Further processing and settling out occur in each reservoir along the waterway. Flooding of the lower river

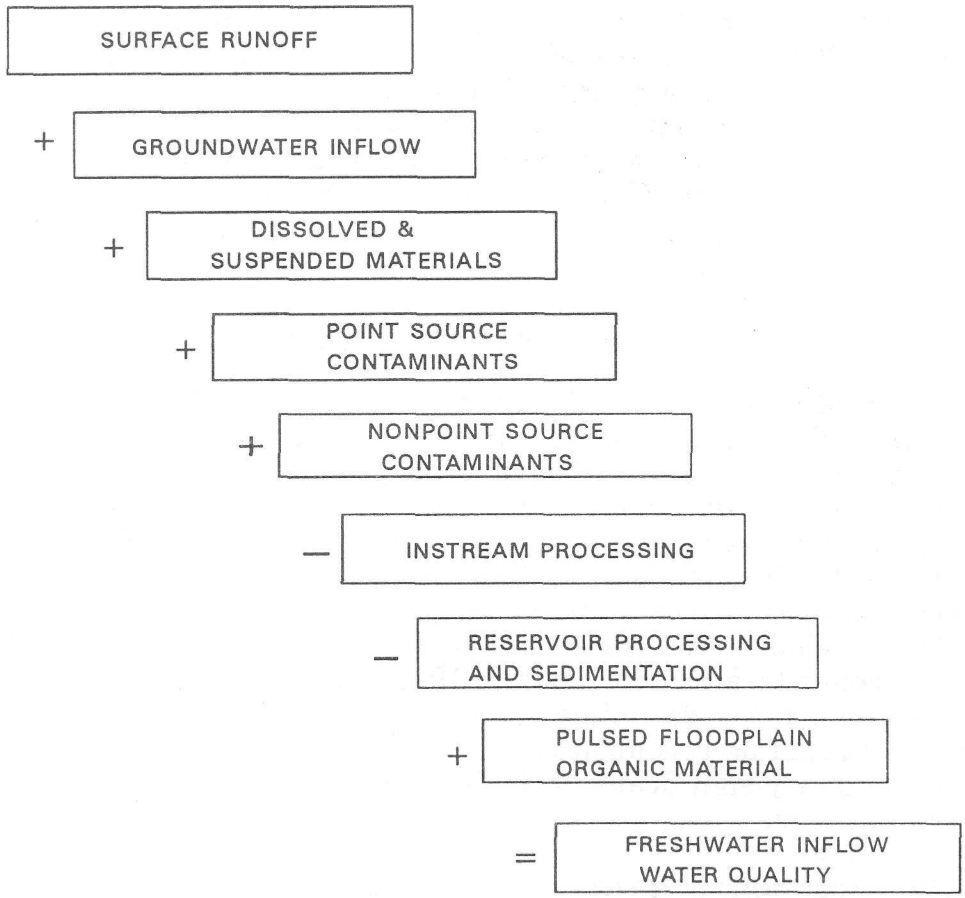


Figure 5. The determinants of water quality. Contaminants are added or removed from stream flow as it moves to the bay.

floodplain periodically introduces pulses of organic material from the forest floor into the river. Water quality may both degenerate and regenerate during passage through various river segments before entering the bay.

The Texas Water Commission establishes water quality criteria and inventories waters of the state biennially (TWC, 1990). When dissolved oxygen levels are below 3 mg/L, a stream segment or other water body is deemed not fishable (that is, unable to support fishes due to lack of oxygen). When fecal coliform bacteria exceed 200 per 100 ml the stream is not swimmable (due to bacterial contamination). A number of Trinity and San Jacinto river segments and coastal streams have been designated as not swimmable; some San Jacinto river segments are not fishable. Numerous headwater tributaries continue to maintain high water quality, but large stretches of the Trinity River and its tributaries exhibit poor water quality, particularly in the vicinity of the Dallas-Ft. Worth metropolitan area. Low dissolved oxygen, bacterial contamination, and nutrient enrichment are persistent problems. Several reservoirs act as waste treatment components, with downstream water of higher quality than incoming flow. Similar circumstances can be found in the San Jacinto basin and several coastal basins associated with the bay. Some stream segments are among the worst in the state. Dissolved oxygen levels frequently decline when passing through urban areas. Stanley (1989) noted that the oxygen sag for the Trinity River extended 300 miles, from Ft. Worth to Lake Livingston. It appears that Lake Livingston, constructed primarily as a source of drinking water for Houston, currently functions as a large, and effective, sewage treatment plant and nutrient sink. Contaminants from the Dallas-Ft. Worth metropolitan area are reduced during the long journey to the bay. Contaminants from the Houston metropolitan area, and the industrial corridor along the Houston Ship Channel, enter the bay without significant reduction.

The Estuarine Landscape

The landcape concepts remain valid in the estuary. Most of the watershed is sub-aerial. The majority of the estuary is submerged (sub-aqueous). Patches of differing habitat are prominent along the shoreline and across the bottom of the estuary; they are present, but quite subtle, in the water itself. Recreational fishermen search for patches of clear "green water" where artificial lures can be seen by visual-feeding fishes. Other patches are "slicks" that exude a "watermelon" odor attractive to predaceous fish, a phenomenon undescribed by scientists. The possibility that these slicks may be produced by tidally-mixed fronts or convergent zones (Mann and Lazier, 1991) that concentrate floating organic matter on the surface, damping small waves, has not been investigated. Corridors now stretch as greenbelts along the shoreline and small tidal streams. Edges are particularly significant in the estuary, sought by planktonic larvae and patrolled by predators.

The estuarine ecosystem is a composite of strikingly different types of habitats. The largest of these habitats is the 3-dimensional (length, breadth, and depth) <u>open-bay water</u> component to which all other habitats are linked. Equally large in areal extent but virtually 2-dimensional (length and breadth), is the underlying open-bay bottom component. The bottom functions as a matrix in which two distinct types of habitat patches can be found. On hard bottoms with strong currents, patches of oyster reef rise up to provide the only hard substrate and elevated surface above the bay bottom. On softer sediments in shallow water, patches of submerged aquatic vegetation, the subtidal seagrass meadows, can be found near the periphery of the bay. As the bay bottom slopes upward at the edge of the bay, meadows of intertidal vegetation, the peripheral marshes, punctuate the shoreline. Some low-sloping shore zones do not support emergent vegetation but form the intertidal peripheral mud flats. Patches of very soft, unconsolidated subtidal bottom are scattered within various shoreline wetlands to create the peripheral marsh embayments. This conglomerate of habitats is connected upstream to the freshwater riverine/floodplain habitat and downstream to the marine waters of the nearshore gulf, and via migratory birds, to the interior of the continent.

A simplified web of connections between these estuarine habitats is shown in Figure 6. Four habitats are essentially self-sustaining producer or autotrophic habitats - the open-bay water, marsh, seagrass, and mud flats. The dominant producer organisms are indicated - phytoplankton, benthic algae, marsh grasses

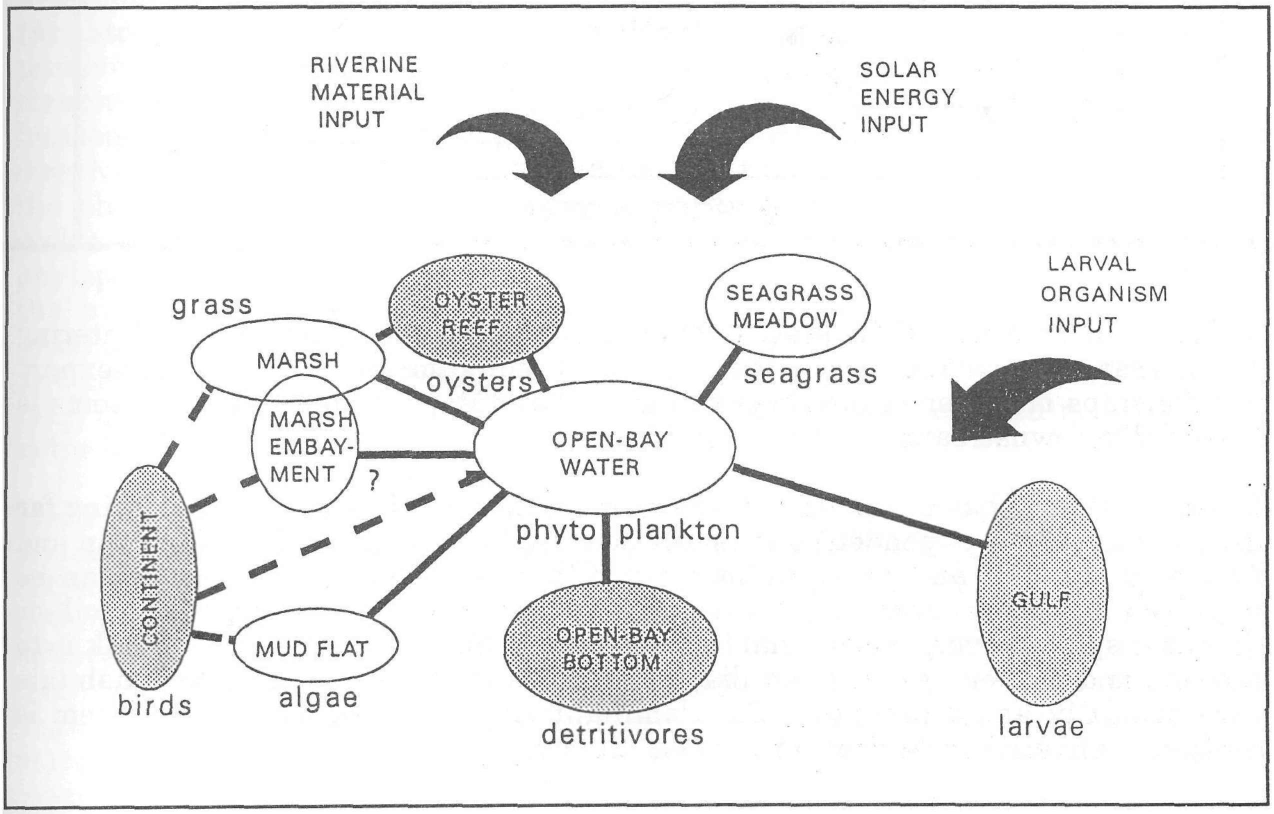
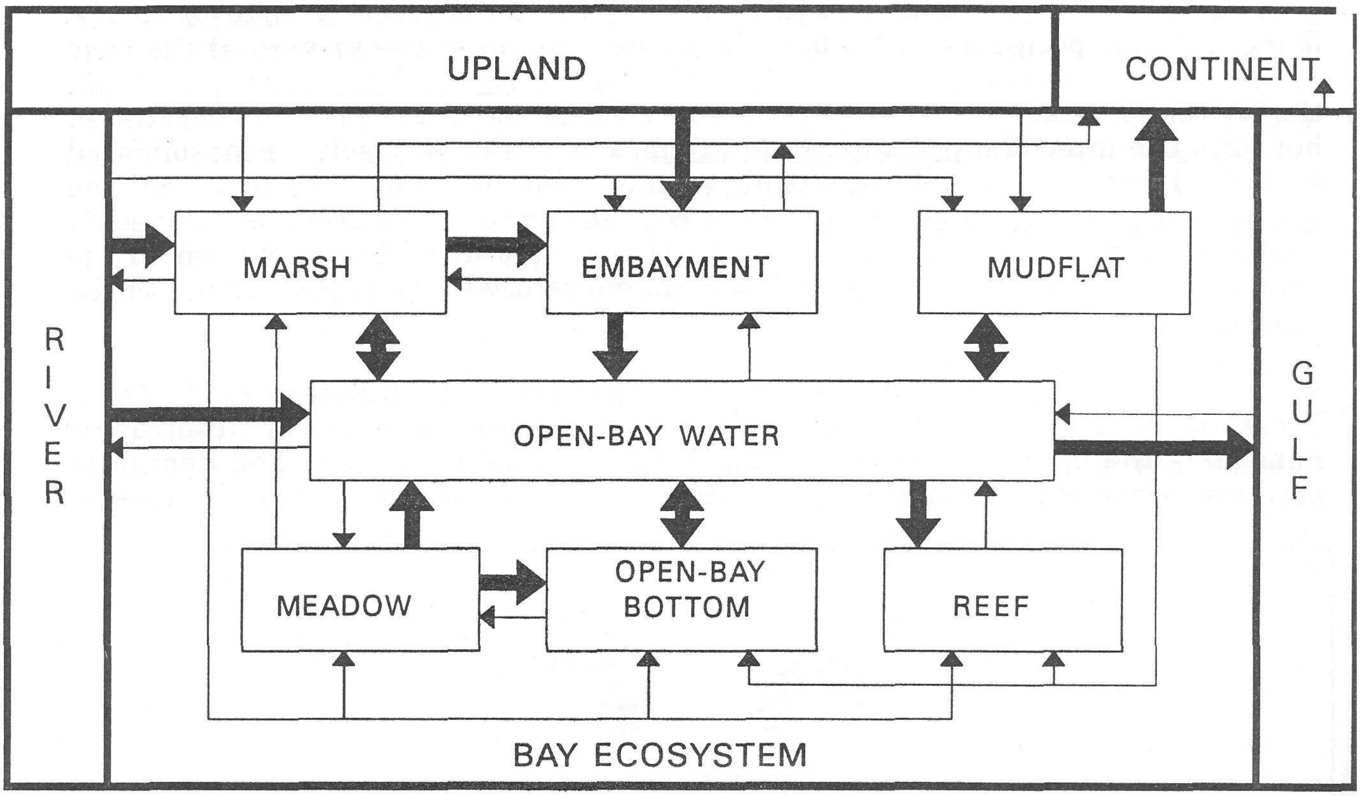


Figure 6. The web of estuarine habitats, indicating the dominant producer organisms of autotrophic habitats (open ellipses) or consumers in heterotrophic habitats (shaded ellipses). The principal external inputs are also indicated (arrows).

Figure 7. The import-export relationships between habitat components of the bay ecosystem and adjacent ecosystems. Major material flow is shown by a heavy line, moderate flow by a thin line; minor flows have been omitted.



rather than producers. The status of marsh embayments is uncertain. Wintering or migrating continental birds are also consumers. The import-export relationships of material flow between these habitats and adjacent ecosystems is essentially downstream, as shown in Figure 7.

In summary, the bay ecosystem can be greatly influenced by activity occurring far from the bay. It is dependent on distant actions, like the spawning of shrimp and finfish in the gulf and precipitation runoff from a remote watershed. It can be impaired by other actions, for instance, waste water discharge and oil or chemical spills. Seven distinct habitats comprise the bay ecosystem and link it to riverine and gulf ecosystems and distant portions of the continent. These habitats vary spatially and temporally. The dominant characteristic of the ecosystem is continual physical, chemical and biological change.