Chapter 1

TIDAL FRESHWATER WETLANDS - AN INTRODUCTION TO THE ECOSYSTEM

Andrew H. Baldwin, Aat Barendregt & Dennis F. Whigham

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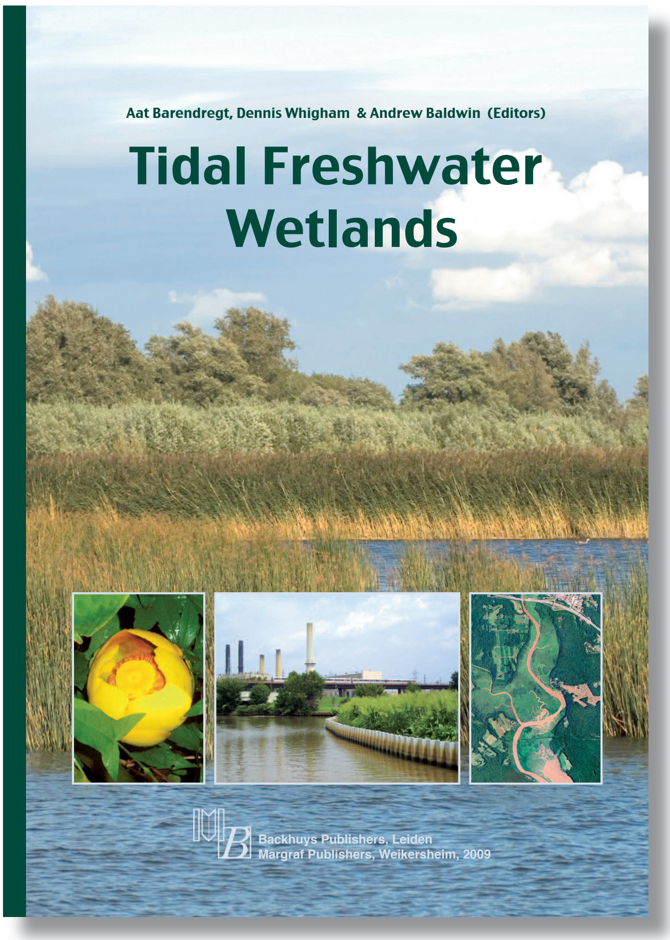

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TABLE OF CONTENTS

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Chapter 1

TIDAL FRESHWATER WETLANDS - AN INTRODUCTION TO THE ECOSYSTEM

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Abstract: Tidal freshwater wetlands are among the most productive ecosystems on earth and are more species-rich than other types of coastal wetlands. However, they have received less attention than saline coastal wetlands such as salt marshes and mangroves. In this chapter we present an overview of the tidal freshwater wetland (TFW) ecosystem as a precursor to the more detailed chapters that follow. TFW developed in many estuaries worldwide during the last 5,000-6,000 years, particularly in coastal plain estuaries. They have been used as valuable sources of food and shelter by humans for essentially their entire existence, and many large cities have developed in or near TFW. The landscape position of TFW is at the upper end of the estuary where river discharge is sufficient to prevent intrusion of saline water but where tidal influence still extends. The dominant physical processes governing the development and persistence of TFW are tides and sedimentation, which determine the geomorphology and hydrodynamics of the estuary and its wetlands. As in all wetlands, TFW are characterized by saturated soils that lead to the development of anaerobic, chemically reducing conditions. Furthermore, plant productivity is high and decomposition rates low for some species and very high for others, the net effect resulting in the development of organic soils in TFW. High primary productivity and physical habitat provided by plants support productive and diverse communities of aquatic and terrestrial animals, including invertebrates, fish, birds, reptiles, mammals, and amphibians. These organisms form complex food webs that link TFW to adjacent terrestrial and aquatic ecosystems. Because of the increasing recognition of the importance of TFW for humans and ecosystems, efforts to restore and conserve TFW have been initiated. However, the future of TFW under current scenarios of global changes in sea level, temperature, precipitation, atmospheric carbon dioxide, and eutrophication is uncertain.

Keywords: tidal freshwater wetlands, North America, Europe, geographic distribution, estuary, human use, hydrology, tides, sedimentation, biogeochemistry, plants, animals, invasive species, restoration, conservation, global change, sea level rise

INTRODUCTION

In northwestern Europe and eastern North America the tidal freshwater zones within estuaries were historically locations for the establishment of human settlements. Many large and important cities (e.g., Philadelphia, Washington, Richmond, Hamburg, Rotterdam, Bordeaux) were established in the tidal freshwater zone, in part because it was the most inland point in the estuary that could be reached by ships. These areas were ideal, sheltered locations for the establishment of international trade and served as hubs for economic connections with the upstream areas within and beyond the river watersheds. The development of urban centers and port facilities resulted in the loss of tidal freshwater habitat as did the reclamation of wetlands for industrial development and agriculture. Another major consequence of urbanization was the discharge of human and animal wastes as well as chemicals associated with industrialization and agriculture. The location of the tidal freshwater zone within the estuarine system also meant that tidal freshwater wetlands (hereafter referred to as TFW) were areas of high rates of sedimentation of suspended matter generated in part by human activities in the watershed.

Not all areas were equally impacted by historical patterns of development, particularly in eastern North America, where many TFW were not in regions heavily settled by European immigrants. As a result, some areas were minimally impacted by human activities. In modern times, considerable efforts have been made to protect the remaining wetlands within the tidal freshwater zone and restoration efforts have been initiated in other systems. Furthermore, the tidal freshwater zone is less eutrophic in many parts of eastern North America and northwestern Europe than some decades ago because of efforts to control losses of sediments and nutri-

Tidal Freshwater Wetlands, pp. 1-10
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ents from farms and provide secondary and tertiary treatment of wastewater before it is discharged into coastal rivers.

Many books and articles have focused on estuaries (e.g., Fairbridge 1980, McLusky & Elliott 2004, Dyer 1979, Knights & Phillips 1979, Wolfe 1986, Nordstrom & Roman 1996, Nedwell & Raffaelli 1999, Hobbie 2000), but few have synthesized information on ecosystems in the tidal freshwater zone of North American and European estuaries. Research on European TFW started in the 1950s. One of the largest areas, the Biesbosch in The Netherlands, was investigated for its soil development, vegetation, and hydrology (Zonneveld 1960); one year later a book in the Dutch language also incorporated the history and fauna of this region (Verhey et al. 1961). A comparable set of investigations was performed from Hamburg in the TFW of the Elbe estuary on the physical processes, fauna, and flora (e.g., Kötter 1961). In the period 1955-1975 a set of publications was published in Archiv für Hydrobiologie (series 'Untersuchungen Elbe Aestuar') on the ecology of TFW, with many publications on hydrobiology. In the nineties a series of investigations was initiated in the Scheldt estuary by Antwerp University. In a special issue a great number of publications about the TFW all over Europe were published (Meire & Vincx 1993). A recent review of the Scheldt estuary was edited by Meire and Van Damme (2005). In North America, more attention has been given to ecosystems in the tidal freshwater zone (although still less than for salt and brackish marshes) and several synthetic articles have been published, beginning in the 1970s (e.g., Good et al. 1978, Simpson et al. 1983a, Odum et al. 1984, Odum 1988; also see chapter on tidal freshwater marshes in Mitsch & Gosselink 2000 and the bibliography by Yozzo et al. 1994). Gosselink (1984) wrote a comprehensive review of coastal marsh ecosystems of the Mississippi River delta plain in Louisiana, including the vast tidal freshwater and oligohaline marshes present there.

The valuation of ecosystem services on a global scale has demonstrated the importance of estuaries and wetlands (Costanza et al. 1997), and TFW have many characteristics that indicate their high ecological and socioeconomic value. Recently a book summarizing the literature on forested tidal freshwater wetlands of the southeastern USA was published (Conner et al. 2007). Finally, we have written three book chapters that provide overviews of TFW ecosystems and their restoration (Barendregt et al. 2006, Whigham et al. 2009, Baldwin et al. 2009).

The goal of this chapter is to provide a broad overview of the TFW ecosystem with the intent of introducing the reader to the topics dealt with in detail throughout the rest of this book. Specifically, in this chapter we first describe the global distribution of TFW, including identifying regions of the world lacking information on the extent of TFW. Then we describe the landscape position of TFW and salinity dynamics in estuaries as they pertain to TFW. Next we outline the physical processes that are fundamental to the establishment and maintenance of TFW ecosystems, including tides and sedimentation, and the biogeochemical environment of TFW and estuaries. An overview of plant and animal communities of TFW follows, including the types of habitats created by hydrological and geomorphological processes of the TFW ecosystem. The range of historic and current human impacts on the TFW ecosystem are then discussed before we summarize the state of restoration and conservation of TFW and how global change may affect these ecosystems.

GLOBAL DISTRIBUTION

No global inventory of TFW exists. Almost all of the information that specifically references TFW, either published in refereed articles or books or in reports and web sites, comes from temperate North America and Europe. For this reason, and because of our professional experience in these parts of the world, we restrict the focus of this book to North American and European TFW. However, there are several sources of information from which the presence of TFW in other parts of the world can be inferred. Specifically, reports and books that include descriptive information on the hydrogeomorphology of rivers, including the upstream limit of tidal influence and extent of floodplains, and general descriptions of ecologically significant wetlands, can be used to identify areas where TFW are likely to occur. Furthermore, the recent availability of satellite imagery via web servers such as Google Earth, in conjunction with hydrogeomorphology data, has made it possible to identify regions where significant TFW probably exist.

In this section we describe the distribution of TFW in the northern temperate regions of Europe and North America, but also summarize what is known about the tropics and the southern hemisphere.

Northern temperate region

In Western Europe TFW occur in, at least, the estuaries of the rivers in northwest Europe (e.g., the Elbe of Germany) to southwest Europe (the Gironde of France and the Minho of Portugal), as well as in British and Irish estuaries (Meire & Vincx 1993) (see: Chapters 2, 6, and 22). On the Atlantic coast in North America, tidal freshwater wetlands occur in all major river systems from the Gulf of St. Lawrence to Georgia (Odum et al. 1984), and are vast in the delta plain of the Mississippi River in Louisiana (Gosselink 1984, Mitsch & Gosselink 2000). Tidal freshwater wetlands also occur on the Pacific coast of North America (Boule 1981, Tanner et al. 2002), including the San Francisco Bay-Delta and Oregon, Washington, Alaska, and southeastern Canada (see: Chapters 4, 13-16, and 19). These wetlands are all associated with coastal rivers in coastal plain regions with flat topography and where the tidal wave propagates many kilometers inland, conditions that promote sedimentation, river meandering, and the development of TFW.

The TFW that occur in upstream portions of large river deltas in microtidal environments, such as the delta of the Mississippi River in Louisiana, USA (see: Chapter 15), dif-

Figure 1. Satellite photos of wetlands in the tidal freshwater zone of the Changjiang (Yangtze) River, about 160 km upstream from the mouth. North is pointing upward. In the left panel the main channel of the river is visible and flows toward the northeast. The large island visible in the river is 8.4 km long, and located at 31º59'38"N, 120º24'54"E. Large tidal wetlands are visible on the northeast edge of the island and on the north side of the spit of land immediately east of the island. The right panel shows a 1-km-wide view of the wetland at the north edge of the spit. In addition to sea walls and rectangular ponds, there is evidence of human activity in the wetland in the right panel, including circular ponds at the middle left and a dammed river canal at the middle right of the photo, both possibly constructed to improve fishing. Photos downloaded using Google Earth Pro and used with permission.

fer considerably in their geomorphology and hydrology from those of estuaries associated with smaller rivers in macrotidal settings. While much research has been conducted on the ecology of Louisiana delta plain wetlands, the freshwater wetlands in this area are rarely referred to as TFW. Many of the delta plain freshwater wetlands do have a tidal signature, but the range is small (< 0.3 m). Also, there is not a clear diurnal pattern of tidal flooding, but rather periodic flooding due to upstream runoff and wind effects, which can alter water level by a meter or more. This pattern of tidal fluctuation is vastly different from those of tidal marshes where tides can fluctuate several meters twice daily.

We have found no information specifically mentioning TFW in temperate Asia, likely due in part to differences in terminology or our inability to search for or read non-English publications. One of us (DFW), for example, has seen herb-dominated TFW on the island of Hokkaido and forested tidal freshwater wetlands in Okinawa, both in Japan. In coastal regions with flat topography, meandering rivers, and sufficient sedimentation rates, or in large river deltas, it is likely that extensive TFW developed during the same time as TFW developed in Western Europe and North America, i.e., during the middle to late Holocene epoch. Satellite photos of coastal regions in eastern temperate Asia (China, Korean peninsula) (in our case viewed using Google Earth Pro) show that vast flat coastal plain areas with meandering rivers exist, and that some wetlands are associated with these rivers in the tidal freshwater zone. For example, tidal limit of the Changjiang (Yangtze) River in China is about 400 km upstream of the mouth at low river discharge conditions (Shen et al. 2000 in Uncles et al. 2002), and wetlands with dendritic tidal channels are visible in satellite images (Fig. 1). Salinity intrudes only about 85-125 km during low flow (Schuebel et al. 1986). However, in many locations evidence of dense population activity, for example rice farming and urban development (Fig. 1, left panel) or physical wetland alteration for fish or shellfish harvest (Fig. 1, right panel), exists in satellite photos that appears to have displaced or altered the vast majority of wetlands. This appears true of coastal wetlands along at least the Yangtze and Yellow Rivers in temperate China and along major rivers of the eastern Korean peninsula.

Tropical region

Almost nothing has been reported in the refereed literature specifically for TFW of the tropics, including their distribution. However, there are several sources of information on the distribution of tropical wetlands from which the presence of TFW can in many cases be inferred. In one of the only comprehensive attempts to assess the distribution of any type of wetlands in the tropics, in the 1980s the International Union for the Conservation of Nature (IUCN) developed a series of reports summarizing information available on wetlands of Asia, Africa, the Middle East, the Neotropics (South and Central America and the Caribbean), and Oceania (Pacific Islands). As part of the Global Wetland Initiative of the International Water Management Institute (IWMI), these reports have been made available online[1]. For Southeast Asia,

[1] http://www.iwmi.cgiar.org/wetlands/WetlandDir.asp

the Asean Regional Centre for Biodiversity Conservation (ARCBC) has created a map-based search tool that links to the IUCN reports for individual wetland areas[2].

Based on descriptions of wetlands in these reports, it appears likely that vast TFW exist in tropical Asia, Africa, and South America. Examples include the deltas of the Irrawaddy River in Myanmar, where tidal influence extends 290 km inland, the Niger River in Nigeria, and the Amazon River in Brazil. In the Amazon River tidal fluctuations in water level can propagate 735 km upstream of the river mouth or farther (Officer 1976, Uncles et al. 2002). Since the high discharge of the river prevents intrusion of salt water into the river (Gibbs 1970), TFW are likely extensive in the lower Amazon basin. Satellite photos (again from Google Earth Pro) show large vegetated islands laced with the dendritic channels typical of tidally-influenced wetlands between about 100 and 300 km upstream of the river mouth (Fig. 2).

As for marshes in the temperate zone, within mangroves there is a gradient from saline systems at the coast to freshwater systems upstream. The salinity gradient results in zonation of mangrove species along the estuary, particularly in Asia where the flora of mangrove forests is most species-rich (Tomlinson 1986, Duke 2006). Some of these mangroves may occur in the tidal freshwater zone, for example the forests dominated by *Bruguiera sexangula*, *Sonneratia caseolaris*, *Barringtonia* spp. and *Hibiscus tiliaceus* described by Bunt et al. (1982). In this study of several rivers of North Queensland, Australia, mangrove forests extended into the tidal freshwater zone of most of the rivers, and in one river, the Pascoe, extended far upstream of the measured salinity limit.

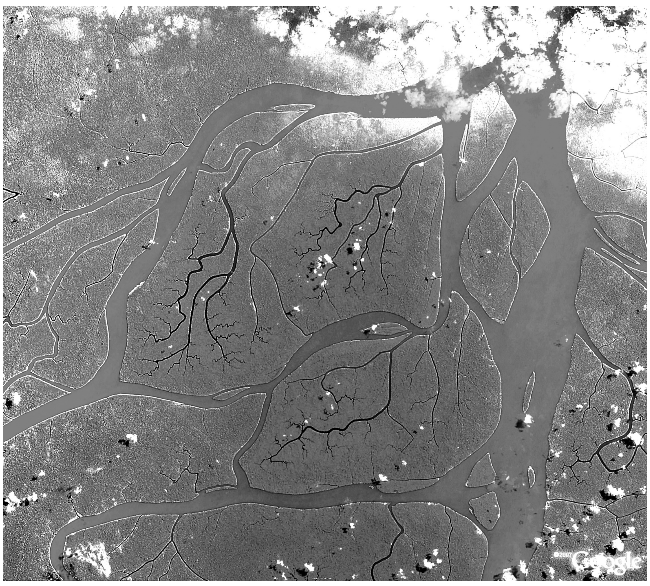

Figure 2. Large wetland islands visible in a satellite photo of a portion of the Amazon River about 200 km upstream of the mouth in the tidal freshwater zone. North is pointing upward. The largest, upper island is about 21 km long and is located at 0º47’05”S, 50º54’39”W. No evidence of human alteration of these wetlands is visible. Photos downloaded using Google Earth Pro and used with permission.

[2] http://www.arcbc.org.ph/wetlands

Southern hemisphere

Very scarce data are available from the temperate parts of the southern hemisphere. Junk (1983) reported that tidal freshwater systems occur on the Atlantic coast of South America but he offered no details on where they occurred, nor their extent. Satellite photos indicate that extensive wetlands occur at the delta of the Paraná River at the head of the Rio de la Plata estuary (Argentina-Uruguay border), which drains the second largest watershed in South America and where tidal influence extends about 320 km inland (Uncles et al. 2002) (Fig. 3). Salinity level at this location in the estuary is < 0.5 ppt, indicating tidal freshwater conditions (Piccolo & Perillo 1999). Some other convincing indications of the presence of TFW in South American estuaries are mentioned in Kandus and Malvarez (2004) and Perillo (1999) and features of a specific TFW in Argentina are found in Pratolongo et al. (2007). Some rivers in South Africa (Allanson & Baird 1999, Schumann & Pearce 1997) and Australia (West & Walford 2000) may contain TFW as well.

Figure 3. Tidal freshwater wetlands at the delta of the Paraná River in the upper Rio de La Plata estuary, Argentina (34º11’40”S, 58 º22’51”W). The area shown in the figure is 5.7 km wide. Buildings and plantations are visible along the natural levees of the distributaries. Photos downloaded using Google Earth Pro and used with permission.

LANDSCAPE POSITION AND SALINITY REGIME

An estuary is "an inlet of the sea reaching into the river valley as far as the upstream limit of the tidal rise" (Fairbridge 1980). Within estuaries, TFW are restricted to the portion of the estuary where there is tidal action but little or no salinity. Depending on the magnitude of tidal energy, river discharges, and topography, fresh water tidal areas (< 0.5 parts per thousand (ppt), sometimes referred to as practical salinity units (psu)) can be present between the highest point of tidal reach (i.e., the head of the estuary) and the oligohaline upper estuary with 0.5 - 5 ppt salinity (McLusky 1993). In some settings, tidal fresh water areas can be found 150 km from the mouth of the estuary (Van Damme et al. 1999) or farther (e.g., the Amazon).

Various definitions of an estuary have been discussed by Elliott and McLusky (2002). A critical aspect of the development of the estuary concept over time is a shift from defining the upstream limit of the estuary as the boundary of saline water intrusion (e.g., Pritchard 1967) to the limit of tidal influence (e.g., Den Hartog 1971, Fairbridge 1980). Only in the latter are TFW considered to be part of the estuary. A confusing term from the Water Framework Directive of the European Union is the definition of the "transitional waters" for the estuaries, consequently neglecting the special conditions of TFW. Similarly, other terms such as "coastal" or "estuarine" are sometimes applied to TFW, but without report of salinity regime identification of TFW is difficult.

Only certain types of estuaries contain conditions suitable for the development of TFW. A number of classification systems have been developed, which are discussed in detail in other books focusing on the hydrodynamics and geomorphology of estuaries (e.g., Savenije 2005, Bianchi 2007). Based on these classifications, estuaries classified as coastal plain estuaries, the most well-studied type, are likely to support TFW. These are estuaries that occur on low-relief coastlines in former river valleys (cut during the Pleistocene), such as the Chesapeake Bay, Yangtze, Thames, and Delaware Bay estuaries (McLusky & Elliott 2004, Bianchi 2007). The TFW in these estuaries formed during the middle to late Holocene epoch over the past 5,000-6,000 years as sea levels rose since the last glaciation (Mitsch & Gosselink 2000, Bianchi 2007). Other types of estuaries that may support TFW include deltas at the mouths of large rivers in microtidal environments (amplitude < 2 m), such as the Mississippi, Yellow, and Nile Rivers, and "tidal river estuaries" that have high river discharge that allows little or no intrusion of seawater into the mouth, but where tides still extend far inland, such as the lower Amazon and the Rio de La Plata (Bianchi 2007). Types of estuaries that are unlikely to contain TFW include rias (drowned river valleys in regions with high topographic relief, e.g., cliffs or mountains) and fjords (glacial valleys in high-relief areas) (Bianchi 2007). Several other types of estuaries exist that may or may not support TFW, depending on their hydrogeomorphology.

The location of the tidal fresh water zone within the estuary depends on the balance between water volume and velocity of the incoming tide and the discharge of the out-flowing river. Tidal characteristics are strongly dependent on river discharge: in rivers with high discharge, the tidal limit may be much farther downstream than in low discharge (Fig. 4). Additionally, the discharge determines the degree of vertical salinity stratification, length ("steepness") of salinity gradient, and the length of the tidal freshwater zone (Fig. 4).

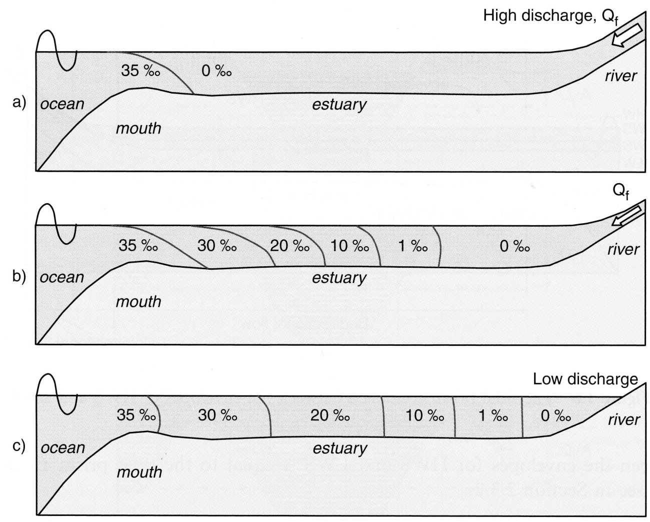

Figure 4. Bottom topography and longitudinal distribution for coastal plain estuaries that are (a) stratified, (b) partially mixed, and (c) well-mixed. Note that coastal plain estuaries have flat bottom topography (not sloped as they are often depicted) and that the salt intrusion length and pattern of stratification are influenced by river discharge (Q). Reproduced from Fig. 1.7 of Savenije (2005) with permission.

PHYSICAL PROCESSES: TIDES AND SEDIMENTATION

Physical processes are of overriding importance in determining the geomorphology, biogeochemistry, and ecology of TFW. Enormous quantities of water flow in and out of TFW twice a day, creating alternately flooded and non-flooded conditions throughout these wetlands. At certain locations erosion may result but the flooding tides also bring in sediment. The combined effects of tide-driven erosion and sedimentation determine hydrogeomorphological conditions.

Tides

Tides are the dominant and best-studied hydrologic feature of estuarine wetlands, and the bulge of water that flows into and out of estuaries is called the tidal wave (Officer

1976, Savenije 2005). Tides are due to the combined effects of the gravitational attraction between the sun and moon and the oceans. During the new moon phase of the lunar cycle, the sun and moon pull together on the oceans, creating a bulge, or high tide, on that side of the earth. Simultaneously, another bulge occurs on the opposite side of the earth because earth is essentially pulled away from the water on that side due to decreasing gravitational pull with increasing distance from the moon. This is why there are about two high tides per day (semidiurnal tides), even though the earth only turns once a day. Similarly, during the full moon phase, the sun and moon are pulling from opposite sides of the earth, creating a bulge on each side. Both of these positions of the sun and moon create tides of the greatest amplitude (difference between low and high tide), referred to as spring tides. When the sun and moon are more or less at right angles, during the first and third quarter phases, they are not pulling together, and tidal amplitude is at its lowest. These low-amplitude tides are called neap tides. The amplitude of tides at a particular location depends on the geomorphology of the estuary and coastline.

Progressing upstream in estuaries the flood stage of the tide (i.e., the incoming rising tide) becomes increasingly shorter in duration and higher in current velocity than the ebb stage of the tide (the outflowing falling tide). As for amplitude, the duration and velocity of ebb and flow stages depends on the geomorphology of the estuary and coast, and the amplitude can increase to 6 m or higher in the tidal freshwater zone of the estuary. In general, the greater the amplitude of the tides at the mouth of the river, and the less steep the river gradient, the farther upstream the tidal wave will propagate. However, eventually the wave decreases gradually in amplitude and velocity against the gradient of the river, and the system becomes non-tidal.

While tides are critical to the development of TFW, the water level at a particular TFW is also influenced by river flow and wind speed and direction. Wind may cause water level fluctuations greater than diurnal tide, for example during storms or in microtidal areas such as the delta plain of the Mississippi River in Louisiana (see: Chapter 15).

A considerable body of literature exists on tides and estuarine hydrology, and the reader is directed to works such as Officer (1976), Savenije (2005), and Wolanski (2007) that have treated this subject in detail. While we include no specific chapter on hydrology of TFW, the overriding influence of tidal hydrology on the characteristics of TFW is evident throughout this book, and estuarine hydrology as it relates to aquatic productivity is treated in some detail in Chapter 11.

Sedimentation processes

In contrast to salinity, which changes in a unidirectional way, suspended matter concentrations often show a clear maximum near or in the fresh water tidal zone, referred to as the Estuarine Turbidity Maximum (ETM) and as illustrated in Fig. 5 (also in, e.g., Meade 1972, Grabemann et al. 1997, Mohd-Lokman & Pethick 2001, Uncles et al. 2002, McManus 2005; see: Chapter 11). Two processes are responsible for the high turbidity. First, saline water has a higher density than fresh water, and it therefore tends to remain at the bottom of the channel and form a wedge as it moves upstream during a tidal cycle, depending on mixing and river discharge (Fig. 4). During the change in tides, the upper fresh water flows downstream and the saline bottom-water flows upstream, facilitating the development of boundary conditions. At the tangent plane where the two flows meet, the velocity is zero, without physical disturbance, and the concentration of suspended matter appears to be the highest (Officer 1981). Second, at the same location, physical-chemical conditions occur that result in the flocculation of suspended particles, increased by the input of particles from the brackish zone. This flocculation of suspended particles is stimulated by the differences in electric charge in the particles, which is optimal at very low salinities (Eisma et al. 1994). As a result, the concentration of suspended particles is highest in the tidal freshwater zone just above the brackish zone (i.e., at the salt front or salt wedge; Meade 1972).

The high concentrations of suspended particles at the ETM result in high rates of sedimentation in TFW compared with more saline coastal wetlands. Furthermore, high sedimentation rates promote soil genesis, since the intensive sedimentation rates in TFW create clay soils rich in organic material and nutrients (Zonneveld 1960).

During flood events, settling of sand occurs mostly along the banks of the main river channel and tidal channels, creating a zone of slightly higher elevation than the rest of the wetland that is known as a natural levee. These natural levee areas drain more quickly and are subjected to lower flooding depth and frequency, often leading to the development of distinct plant communities. Finer particles remain suspended in the flooding water longer than sands, with silt particles

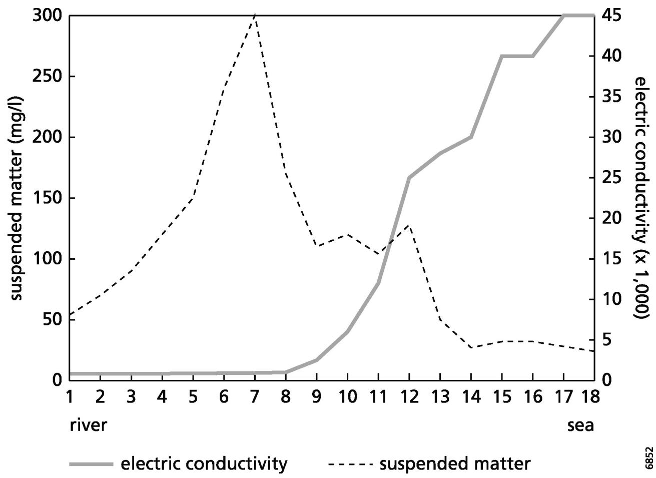

Figure 5. Electrical conductivity (µS/cm) and suspended matter (mg/l) in the estuary across the gradient from the river to the mouth. Data derived from the Scheldt River (Van Damme et al. 1999).

and then clay particles settling out at progressively greater distances from tidal channels. The sedimentary processes in TFW are explored in greater detail in Chapter 4.

Sedimentation processes interact with chemical and biological processes in complex ways within the TFW system (Pasternack et al. 2000). Observing the system on a watershed scale, TFW are part of a chain starting or continuing (Jordan et al. 2008) from the discharging river water, rich in nutrients and organic matter, into the TFW and then continuing into the brackish section of the estuary. Due in large part to the location of the ETM, the tidal freshwater zone appears to be where a major part of the organic and inorganic nutrients are removed or recycled. Nitrogen and phosphorus (e.g., Bowden 1984a, Khan & Brush 1994, Uncles et al. 1998, Jordan et al. 2008), organic carbon (Findlay et al. 1991, 1998b), and silica (Struyf et al. 2005a) are transformed or removed from overlying water as it flows into and out of TFW over several tidal cycles. Due to nutrient-rich conditions, the mixing tidal flows, and the sedimentation of suspended matter, conditions are optimal for production of terrestrial and aquatic biomass (see: Chapters 10 and 11) and supporting food webs (see: Chapter 12). Finally, the water flowing into downstream saline sections of the estuary contains reduced levels of nutrients and organic matter but higher levels of dissolved oxygen and bio-available silica.

BIOGEOCHEMICAL ENVIRONMENT

The biogeochemical processes of the tidal freshwater zone of estuaries can be divided into processes occurring under primarily anaerobic conditions, which occur in wetland and estuarine sediments, and aerobic conditions, which occur in the open water of channels and bays. While the biogeochemical processes of wetlands and open water are clearly linked, in the literature they are often treated separately as either wetland or estuarine biogeochemistry (but see: Jickells & Rae 1997). Furthermore, little research has focused specifically on the biogeochemistry of the tidal freshwater zone. Fortunately, much of the research on biogeochemical processes in nontidal freshwater wetlands and saline tidal wetlands can be extrapolated to the tidal freshwater wetlands, and considerable work in estuaries has included the tidal freshwater zone along with estuarine regions farther seaward (e.g., Bianchi 2007).

Dominant biogeochemical processes within estuaries are related to the cycling of organic matter, nitrogen, phosphorus, silica, sulfur, carbon, and trace metals (Mitsch & Gosselink 2000, Bianchi 2007; see: Chapters 11 and 12). Many of the processes are microbially mediated, and in wetlands there are numerous transformations of nitrogen, iron, manganese, and sulfur that are important under the chemically reducing environment generated by anaerobic conditions (Mitsch & Gosselink 2000, Megonigal et al. 2004). Due to the presence of emergent vegetation with aerenchymous tissue, however, oxidizing environments exist around roots due to oxygen leakage (as well as on the soil surface) that promote aerobic chemical transformations. Because of the close proximity of aerobic and anaerobic conditions, diffusion between different biogeochemical environments is possible, facilitating chemical transformation. In tidal freshwater marshes methanogenesis is likely to be a dominant decomposition pathway, in contrast with salt marshes, where sulfate reduction is likely to predominate because of the presence of sulfate in seawater and the greater energy yield from sulfate reduction than from methanogenesis (Megonigal et al. 2004).

The sediments of tidal freshwater wetlands are usually organic due to low decomposition rates of some plant species and low turnover rates of belowground biomass; reported levels of organic carbon in tidal freshwater marshes ranged from 14-68% (Mitsch & Gosselink 2000). Reported nitrogen and phosphorus levels for the same sites are 1-2% and 0.1-0.7%, respectively. Since most of the soil nitrogen is in organic form its concentration is closely related to total organic matter content (Mitsch & Gosselink 2000).

ECOSYSTEM STRUCTURE: ORGANISMS AND BIODIVERSITY

The physical and biogeochemical processes in TFW create temporally and spatially varying opportunities for colonization, growth, and reproduction for plants and animals. The habitats of TFW systems include the river channel itself, mudflats, tidal channels, and wetlands dominated by herbaceous plants (marshes) and woody plants (shrub- and tree-dominated wetlands; often referred to as scrub-shrub and forested swamp systems) (Fig. 6), both of which exhibit variation in species composition along elevation gradients.

Despite the long history of human settlement in or near TFW, the ecology of these systems has not been studied as intensively as have saline and brackish coastal wetlands (Elliott & McLusky 2002). The lack of research focus on TFW has at least three origins. First, marine and salt marsh ecologists have rarely investigated TFW, since the water is fresh and out of their scope. Second, river and nontidal wetland ecologists have rarely been interested in TFW because they are tidal and thus viewed as marine. And third, on a more emotional level, these wetlands may have been viewed as unattractive since there are few species unique to freshwater tidal wetlands and they are often muddy and not easily accessible.

In this section we provide an overview of the plant and animal communities of TFW of North America and Europe. The ecosystems of TFW are described in detail in Chapters 4-9.

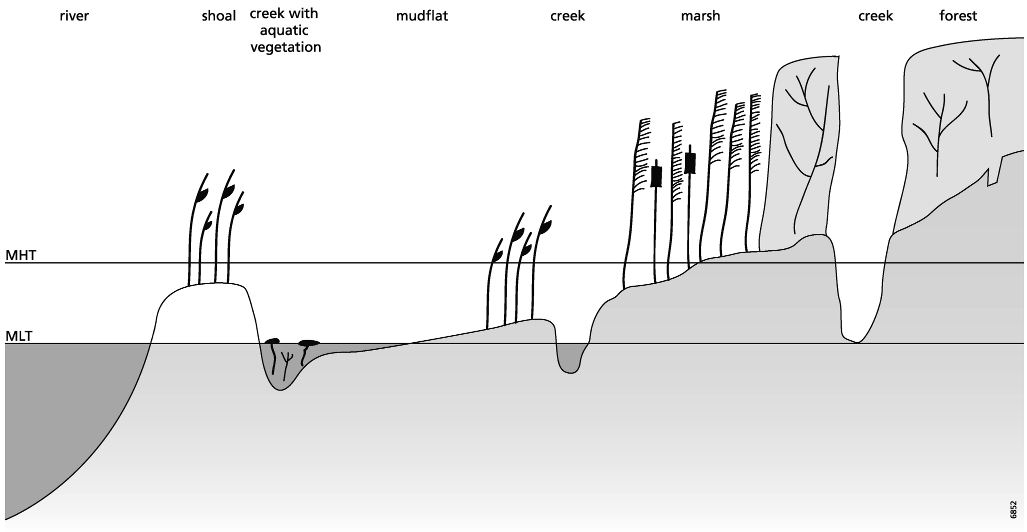

Figure 6. Cross section from the channel to the high marsh/forest in European TFW. MHT = mean high tide level; MLT = mean low tide level.

Plants

The plant communities of TFW of both North America and Western Europe share at least two characteristics. First, they exhibit horizontal zonation in species composition along elevation gradients (i.e., gradients of inundation depth and frequency). Second, they exhibit higher species richness than saline wetlands located farther downstream in the estuary. In contrast, the TFW of North America tend to be more species-rich and temporally variable than TFW of Europe, possibly due to a greater abundance of annual species, and invasive species seem to be more common in North America than Europe (see Chapters 5, 6, and 9). Additionally, the effects of a much longer history of human alteration of wetlands, particularly tidal hydrology, in Europe than in North America are evident in TFW vegetation (see: Chapters 2, 3, and 17).

The herbaceous-dominated marshes of North American TFW share with European systems, among other taxa, the bulrushes (*Schoenoplectus* spp.), cattails (*Typha* spp.) and giant reed (*Phragmites australis*), as well as jewelweed, *Impatiens capensis* (native to North America, non-native in Europe), and purple loosestrife, *Lythrum salicaria* (native to Europe, non-native in North America) (see: Chapters 5 and 6). Annual species are abundant in some TFW of North America, notably on the mid-Atlantic USA coast. A number of studies have documented the importance of seed banks and seedling recruitment to the maintenance of these mid-Atlantic plant communities. In European systems, sedimentation is an important factor in the succession of plant communities, resulting in a successional sequence of *Phragmites*-dominated systems first to systems dominated by other species of herbs, and then to willow (*Salix* spp.) forest, the final stage of succession. These willow-dominated forested systems have historically been managed for production of willow branches by coppicing. The tidal forested systems of eastern North America, in contrast, differ in species composition between geographic locations, can be species-rich, and may exhibit a hummock-hollow microtopography that supports a diverse understory of shrubs and herbaceous plants. However, less is known about the forested tidal wetlands of North America than about the marshes.

Animals

The habitats provided by plants support diverse assemblages of aquatic and terrestrial animals in both European and North American TFW (see: Chapters 7 and 8). As for plants, few or no animal species are restricted to TFW, although some species rely heavily on TFW for at least part of their life cycle. These ecosystems support all of the major groups of animals, i.e., aquatic invertebrates (including zooplankton), terrestrial invertebrates, fishes, amphibians, reptiles, birds, and mammals. As many as 280 species of birds has been reported from North American TFW (Odum et al. 1984), and some commercially important fish rely heavily on TFW for part of their life cycle, such as rockfish (*Morone saxatilis*) (Mitsch & Gosselink 2000). Water depth affects the distribution of most species, and species assemblages can change throughout the day due to tides. When the tide is high, fish and aquatic invertebrates, and some turtles and wading and swimming birds, forage in the standing water in the wetlands. As the tide falls, many organisms retreat to permanently flooded channels, while others bury in the mud or remain in small pools. At low tide, mudflats are exposed where many birds forage for invertebrates.

ECOSYSTEM FUNCTION: PRODUCTIVITY AND FOOD WEB SUPPORT

Vegetation of TFW has levels of primary production higher than most other ecosystems on earth, with measurements of > 2 kg/m²/yr for aboveground plant biomass reported for a range of different systems (see: Chapter 10). This productivity is due primarily to the location of TFW in the nutrient-rich parts of the estuary and continued input of nutrients in water or sediments via tides. Additionally, productivity remains high throughout the growing season because perennial species reach their maximum biomass early in season while annuals continue to grow and predominate in the middle to late growing season, at least in USA mid-Atlantic marshes. There is also evidence that annual differences in net primary production are less variable in TFW compared to other types of coastal tidal wetlands (Whigham & Simpson 1992).

The high levels of nutrients in aquatic, i.e., open water, portions of estuaries support primary productivity of phytoplankton (see: Chapter 11). The levels of nutrients and productivity in aquatic systems are closely related to tidal hydrology, river discharge, and other physical factors discussed previously. Furthermore, wetland vegetation is an important source of biogenic silica that supports aquatic primary production.

The high primary productivity of the open water and wetland parts of the estuary support a diverse and productive food web (see: Chapter 12). Organic matter in the wetlands can be grazed directly by insects or mammals, or decomposed in the wetland. Tidal exchange provides a mechanism for export and import of dissolved and particulate organic matter. Phytoplankton also contribute to food webs, although the level of production is much lower on an areal basis than for TFW vegetation. Benthic and aquatic invertebrates and omnivorous nekton consume decomposing detritus (primarily) or phytoplankton, which are in turn consumed by fish, mammals, and birds at higher trophic levels.

HUMAN IMPACT

Few TFW in Europe or North America can be described as pristine or undisturbed by human activities, with the possible exception of Alaskan TFW (Chapter 16). As noted previously, TFW occur in a landscape position favorable for human settlement. The negative aspects for humans who settle in TFW include potential flooding and mosquito-borne diseases. Positive aspects are the availability of water for transport and agriculture, the extremely nutrient-rich, easily plowed soils for agriculture (assuming wetlands can be drained or dewatered), and in their original state the abundance of fish, shellfish, mammals, and plants for food and shelter. In Chapter 2 and 3 a review of the historical use of and impacts on TFW is given.

The history of TFW in Europe starts with Neolithic settlement, reported from The Netherlands (Louwe Kooijmans 1987) and UK (Hall et al. 1987, Bell 2000, Momber 2000, Van de Noort 2004). At least 2,000 years ago humans lived in many TFW in Europe. The rise of sea level in the following millennium caused many settlements to be abandoned; however, humans continued to occupy TFW for a major part in the past millennium. We reclaimed and changed the TFW in many countries, e.g. in UK (Knights & Phillips 1979), France (Avoine et al. 1981, Mesnage et al. 2002), Ireland (Healy & Hickey 2002), and Germany (Garniel & Mierwald 1996, Petzelberger 2000). Recently we performed this on a large scale with extensive ports and industry areas (Pinder & Witherick 1990).

Because North America was settled with dense populations much later than Europe, considerably more area of TFW remains. Prior to European settlement, native Americans altered vegetation by creating clearings for agriculture in forests and around villages (Schneider 1996), and undoubtedly harvested fish, mammals, wild rice, and other sources of food and fiber in TFW (Chapter 3). However, their direct impacts on the hydrology or geomorphology of TFW were minimal. European settlement beginning in the 17th century in densely populated villages, towns, and cities resulted in larger-scale timber harvest, alteration, and filling of TFW (Cooper 1995, Baldwin 2004). Odum et al. (1984) state that "almost all of the TFW habitat on the USA Atlantic coast is in the 13 original colonies; much of it lies adjacent to major cities". In urbanized watersheds, such as the Anacostia River watershed in Washington, DC, the vast majority of TFW were lost (Baldwin 2004). However, in less urbanized areas, extensive TFW remain. For example, in the Nanticoke watershed in Maryland and Delaware, about 62% of all types of wetlands, but only 4% of estuarine wetlands, were lost by 1998 due to European settlement (Tiner 2005).

The TFW were not only influenced by physical disturbance during human settlement, but one of the most important conditions, the quality of river water, also changed drastically at many locations. During the last century chemicals in runoff and wastewater have resulted in eutrophication, low dissolved oxygen, and pollution with heavy metals and organic hydrocarbons (e.g., Riedel-Lorjé & Gaumert 1982, Khan & Brush 1994). At present the conditions are improving (e.g., Van Dijk et al. 1994, Van Damme et al. 2005).

ECOSYSTEM RESTORATION, CONSERVATION, AND THE FUTURE OF TFW

In recent decades the importance of wetlands in general has been recognized, and efforts have been made to restore wetlands damaged by human activity, and to conserve existing wetlands, including TFW (see: Chapters 19-22). In particular, TFW have been recognized as important habitat for wetland plants and animals, particularly for the migration of waterfowl and diadromous fish species (e.g., Gosselink 1984, Odum et al. 1984, Mitsch & Gosselink 2000, Ysebaert et al. 2000b, McLusky & Elliott 2004). Additionally, many TFW are located close to major cities, where many people use TFW for recreation or nature observation, and where ecosystem services such as flood storage, storm protection, and water quality improvement can have maximum benefit. Because of the increasingly recognized ecological and socio-economic value of TFW, restoration (see: Chapters 19 and 20) and conservation (see: Chapters 21 and 22) efforts are growing in scope and distribution (e.g., Baldwin 2004, Van den Bergh et al. 2005a).

Successful restoration and conservation of TFW depends on understanding how climate change will affect these systems (see: Chapter 23). Rising sea level will increase the penetration of saline water into estuaries and possibly result in increases in inundation frequency and depth. Furthermore, temperature and precipitation patterns will change, and higher carbon dioxide concentrations in the atmosphere may alter competitive hierarchies among plant species. These changes will shift distributions of plants and animals and affect biogeochemical processes. TFW have some ability to accrete vertically in response to higher water level, and may migrate inland as sea level rises, assuming suitable topography and absence of human structures such as sea walls and bulkheads. However, it is difficult to predict how climate change coupled with habitat alteration and changes in other global processes such as nutrient cycling will alter or affect the persistence of TFW ecosystems.

ORGANIZATION OF THE BOOK

As indicated in the Preface, the goal of this book is to provide a comprehensive review of tidal freshwater wetlands of North America and Europe. To that end, we have organized this book into five parts, each with several chapters. The majority of chapters focus on aspects of TFW in Europe or North America. The separation of the chapters into sections is based on themes. Following the Introduction and two historically-focused chapters, the following six chapters focus on descriptive aspects of TFW. Ecological processes are the focus of Chapters 10-12, and Chapters 13-18 cover TFW in geographically focused portions of NA and Europe. Five chapters (19-23) consider issues such as conservation, restoration, and future development. The final chapter is a retrospective with several recommendations for future efforts to further increase our understanding of TFW. Finally, all of the references cited in the 24 chapters are compiled in the final section of the book. We have also included sixteen pages of color photographs that were chosen to demonstrate the characteristics of TFW in NA and Europe.

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