Tidal Freshwater Wetlands, the Fresh Dimension of the Estuary

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Abstract

Upstream in the estuary, where the river ends, the tidal energy is still present but the constant input from the river creates permanent fresh water conditions. The physical, chemical and biological conditions differ from the brackish part of the tidal area, but by processes from the tidal wave also from the river ecosystem. Just like in the brackish estuary, the variation runs from tidal flats till higher elevated forests. Chemical processes and accretion are prominent, creating wetlands with high turnover. Fertility of the soil and presence of many cities resulted that many tidal freshwater wetlands have been reclaimed. Many characteristic flora and fauna species are represented; biomass is mostly very high. Because this system

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is at the interface of salt – fresh conditions, it can be disturbed soon by sea level rise or global warming.

Keywords
Salinity • Hydrology • River • Vegetation • Zonation • Marsh • Fauna • Fish • Insect • Bird • Mammal • Accretion • Nitrification • Methanogenesis • Sea level rise • Restoration

Introduction

Many papers have described the physical, chemical, and biological conditions in brackish estuaries including the salt marshes. However, most estuaries have another dimension rarely examined where a river with a continuous input of freshwater dominates the conditions and processes in the wetlands. The tidal pulse is equally prominent in this fresh section but most processes and all species are representative of this nonsaline dimension. The brackish section in the estuary is merely the transition between the fresh and salt parts in the same tidal system; many estuarine scientists have neglected the freshwater dimension, and it remains unfamiliar and underrepresented in the scientific literature.

Tidal freshwater wetlands (TFWs) are available for scientific research close to many principal cities. The fresh dimension of the estuary was historically where ships from the sea or ocean made port and where inland river navigation ended and thus the perfect location to start harbors and concomitant urbanization. Principal cities and rivers are linked worldwide to these wetlands. Portland (Columbia), San Francisco (Sacramento), New York (Hudson), Philadelphia (Delaware), Washington DC (Potomac), New Orleans (Mississippi), Hamburg (Elbe), Rotterdam (Rhine), Antwerp (Scheldt), Bordeaux (Gironde), and London (Thames) are examples of cities in the middle of tidal freshwater wetlands. Many wetlands were drained, infilled, and reshaped for economic reasons without paying attention to the ecological values in this ecosystem.

Inattention to the importance of an ecosystem by both the scientific and economic disciplines can result in its loss worldwide. Many tidal freshwater wetlands have been lost to human infrastructure and use, but fine examples are still available to researchers to describe the characteristics of this system. The following text provides a summary of our understanding (mostly from the USA and Europe) of aspects of freshwater tidal wetland ecosystem function and characteristics, known distribution, basic physical and chemical processes, represented flora and fauna, and the future outlook especially with sea level rise. The first descriptions of TFWs with global distribution, biodiversity, and ecosystem functions are by Simpson et al. (1983) and Odum et al. (1984). Recent full reviews are by Barendregt et al. (2009), Conner et al. (2007), and Barendregt and Swarth (2013) and references therein.

The Fresh Part of the Estuary Within the Gradient from River to Sea

The estuary has been classically subdivided to include three parts: the salt section with saline water (polyhaline), the brackish section (mesohaline), and the fresh section with permanently fresh water. Between the fresh and real brackish sections there is, however, an intermediate section with reduced salinity (oligohaline). The energy from the tidal wave that flows upstream and not the water itself is responsible for the mixing of the fresh river and saline sea water to become brackish. This mixing is only partly due to horizontal current flow; there is a vertical mixing processes in the zone where the bidirectional flow of heavier saline tidal sea water meets the overlaying discharging freshwater.

Freshwater hydrology dominates the components in tidal freshwater wetlands, even more so than in other wetlands. Current and tidal water are always present in the aquatic parts, including the sediments and nutrients that are transported with the water. In the semiterrestrial marshes and swamps, this water floods very regularly, causing permanent wet soil conditions irrespective of season. Although sea level induces a fixed water level in the estuary, tidal amplitude creates important daily fluctuations within the limits of high and low tide level, influenced in a 4-week period from the constellation of the moon. Occasionally storm tides elevate sea level and can create irregular differences up to some meters. The effect of fluctuating river water input to water levels in the estuary is mostly buffered by the fixed sea level. The river ecosystem itself is also characterized by water level fluctuations, but the time dimension is different. Periods with high river levels will cause river forelands to be permanently flooded for weeks or months but during a dry period the same areas will be drained for weeks or months. In the latter situation, the groundwater table in terrestrial parts will become subsurface, with soil aeration occurring as a next step.

Tidal freshwater wetlands survive due to the continuous input of fresh river water. When this input diminishes, brackish water intrudes into the fresh system and will with time replace the characteristic freshwater plants and animals with salt-tolerant species. The variation in salinity appears to be the major environmental factor for this change rather than the salinity concentration itself. In the gradient fresh saline, the species diversity is highest in freshwater, diminishes in the brackish section, and increases again with higher salinity (McLusky and Elliot 2004). Input of salinity changes the chemical processes within the wetland, e.g., the reduction of organic matter under fresh conditions takes place with methanogenesis, whereas in brackish conditions sulfate reduction is the basic process (Weston et al. 2011).

Tidal freshwater wetlands thus occur over a limited extent of an estuary. The diurnal tidal wave with permanently high water levels differentiates them from the rivers; the permanent presence of freshwater differentiates them from the other parts of the estuary. Two extra elements have to be added to indicate the special position of these wetlands: the sediments and the nutrients. The rivers transport all residuals

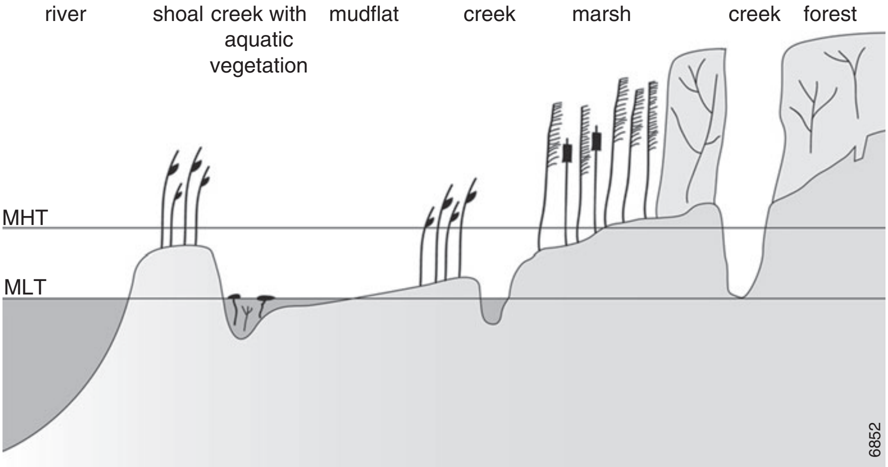

Fig. 1 Cross section from the channel to the high marsh/forest. *MHT* mean high tide level, *MLT* mean low tide level (From: Barendregt et al. 2009, © with permission of publisher)

from overland flow and human activities to the sea, including clay particles, organic components, the natural and human waste, and the free nutrients. The tidal freshwater wetlands are the section where many suspended particles flocculate and produce mud. It can be the area where huge sedimentation occurs; at least it is muddy. Moreover, in this system the nutrients are never limiting. It creates conditions in the fresh section where water, nutrients, and minerals are always present, perfect for biomass production. Within the range of wetlands, this series of vegetation produces high values up to 2 or 3 kg/m^2 dry weight a year.

The Gradient Water–Land Within the Tidal Freshwater Wetlands

Perpendicular to the gradient from fresh to salt, the tidal freshwater wetlands offer a variety of subsystems (Fig. 1), from the deep tidal channel to the upper terrestrial. The basic ecological factor is the elevation of the subsystem relative to the mean high water table; it indicates how many hours the subsystem will be flooded and be deprived of atmospheric oxygen. Hydrology is the main discerning variable. The different subsystems will be discussed to illustrate the variation within the ecosystem.

The very dynamic nature of the aquatic (subtidal) subsystem is a function of the current which is directly related to the dimension of the tidal wetlands and the tidal fluctuation. The potential exits for dynamic currents – for example, a tidal creek that fully floods a wetland of 1 km^2 with 1 m water has to discharge a million m^3 within a few hours. However, most wetlands are a mosaic of flats and higher marshes which reduces the volume and current of water entering and leaving the system. The deep water in the permanent channel might provide perfect conditions for benthic and

Fig. 2 Tidal freshwater wetland in USA, Maryland (Jug Bay) – tidal creek with *Nuphar lutea* and *Zizania aquatica* (Photo credit: A. Barendregt © copyright remains with author)

pelagic species. The benthic species may, however, be confronted with water with high concentration of suspended matter creating unconsolidated sediment conditions. Next to the channel there will be shallow permanent water where dynamics will be reduced and conditions for aquatic plants and benthic fauna are better able to survive.

Higher in elevation is the intertidal subsystem, where tidal water floods for many hours a day. When the current is restricted, sediments can precipitate to form mud flats low in organic matter. Locations low in elevation will be exposed for only a few hours a day and become open mud flats. At higher elevations in the intertidal subsystem, the numbers of hours underwater is reduced and the first semiterrestrial plants can survive. In the USA Yellow spatterdock *Nuphar lutea* and arrow arum *Peltandra virginica* grows in patches; in Europe bulrush *Schoenoplectus* spec. can be present.

One step higher in the elevation will be the real marshes. Where the tidal water still floods for some hours, helophyte species will dominate (Fig. 2), e.g., wild rice *Zizania aquatica* and cattail *Typha* spec. in the USA and reed *Phragmites australis* in Europe. Just higher in the gradient are the high freshwater marshes that will be flooded briefly at high tide under average conditions and for a longer period on spring tides. The soil is rich in organic matter. In the USA these high marshes are extremely rich in species including *Bidens laevis*, *Polygonum arifolium*, *P. punctatum*, and *Hibiscus moscheutos*. In Europe vegetation diversity is also high, e.g., with *Senecio paludosa* and *Calystegia sepium*.

Many locations of the highest elevated (supratidal swamps) subsystem in the tidal freshwater wetlands have a soil that is robust enough to facilitate a vegetation dominated with shrubs and trees. In between the shrubs many plant species are represented. In Europe many of the marshes were managed to grow willows (*Salix* spec.) for wood production, so a change in nature to an organized willow plantation (osier bed). The zone above these shrubs and trees is too high to be flooded and thus not a wetland for this definition.

Distribution and Human Impact

Two basic conditions need to be present to facilitate tidal freshwater wetlands: (1) a tidal wave and (2) permanent riverine freshwater. Global distribution of TFWs appears related to the constancy of river discharges that do not fall below 10–15 % of maximum. When the input of freshwater decreases below this minimum value during a dry or freeze-up period, excessive saline water temporarily enters the system and TFWs cannot develop or persist. Most rivers in the temperate zones discharge at least this minimum in the dry season and potentially support a tidal freshwater wetland (Barendregt and Swarth 2013). Closer to the equator differences between seasonal flows become more extreme. Although the ecological conditions in the landscape are the same, mangroves replace TFWs in the tropical and subtropical regions. Some major tropical rivers, e.g., Amazon and Congo River, discharge freshwater constantly and in volumes that can freshen the ocean for many km from the coast. Although a the tidal wave enters the Amazon for 800 km, indicating conditions for tidal freshwater wetlands may occur, none have been up to now.

Distribution

Basic knowledge on the global distribution and abundance of tidal freshwater wetlands is lacking but beginning to accumulate. North American TFWs occur where rivers meet the ocean along the west and east coasts. The most southerly reported TFWs on the west coast are in San Francisco Bay; and many parts of the extensive 7.5 million ha Yukon-Kuskokwim delta wetlands (Alaska) are tidal and should contain TFWs. Along the east coast, TFWs are well distributed from New Jersey (possibly Canada) to Florida, with a concentration around Chesapeake Bay and in North Carolina. In the Gulf of Mexico, the tidal wave is limited; the extensive tidal wetlands in the delta of the Mississippi are partly impacted by fluctuations in water level from the wind. Excluding Alaska, 200,000 to 1.5 million of ha with tidal freshwater marshes and swamps are estimated to occur in the USA.

Greatly reduced from the amount that would have occurred hundreds of years ago, ca. 15,000 ha with marshes, willow plantations, and swamps are reported in Europe. Most major rivers in Western Europe, e.g., Elbe, Weser, Rhine/Meuse, Scheldt, and Gironde, and those in the UK offer conditions for tidal freshwater wetlands. In the temperate region of South America, at least extensive TFWs are reported from the De la Plata Estuary (Parana River) in Argentina (Kandus and Malvarez 2004). This ecosystem has been reported but not described in Japan and China; and it is likely that the TFWs are well represented in the north of Russia and Siberia and the estuaries of the major rivers in China in which tidal ecosystem can be discerned from Google Earth.

Human Impacts

Tidal freshwater wetlands create for humans a location where many activities have historically taken place. The ecosystem is very rich in fish, waterfowl, and fur-bearing animals to harvest; the marshes are very productive with the input of nutrients from flooding; and freshwater is in abundance. Harvesting of firewood and plant materials for construction was common, e.g., in Europe the bulrush *Schoenoplectus* spec. was harvested to make mats and chairs, and willow *Salix spp.* used for basketwork grew abundantly in osier beds. Native Americans were present in this system 12,000 years ago (Dent 1995) and in Europe a human presence is well documented 5,000 years ago (Van de Noort 2004) and possibly longer (Early Pleistocene). In ancient times settlements were not permanent but this changed with organized societies. In Europe the first permanent settlements arose primarily during the medieval period and locally even earlier in the Roman period. Because flooding was a serious problem that affected infrastructure and the economy of these early settlements established adjacent to tidal freshwater wetlands, the inhabitants started to shape their own environment. First they created small dikes to protect the houses and fields from flooding by closing tidal creeks; and beginning about 1,000 years ago, humans started to reclaim the freshwater marshes for highly valued agriculture fields as an outcome of the dynamic sedimentation within the system.

During last 200 years this process has intensified within and adjacent to tidal freshwater wetlands. Cities have expanded in Europe as well as North America, especially those with harbors close to the ocean or sea. Most of the world's population lives close to the sea for economic reasons, starting at and with the sea harbors. The flat areas of the coastal region, especially in or next to the estuary, were well suited to support the housing, trading infrastructure, and harbors required by the increased economic activity. As a result, many thousands of ha with tidal freshwater wetlands have been occupied, and our present society is generally not aware of the extent of this past activity, e.g., the extensive harbors of Hamburg and Antwerp, and the Ronald Reagan airport in Washington DC, are reclaimed from this ecosystem.

During the twentieth century, pollution in the estuaries has increased primarily from industrial and non-treated human wastewater from the big cities upstream of the estuary. Negative effects on the ecosystems in the Elbe and Rhine Rivers were being reported beginning in the 1930s. Heavy metals and pesticides further deteriorated the ecosystem that was already suffering from extreme levels of nutrient inputs and intensification in human management. Fish stocks have been depleted from overfishing, many estuaries are closed from the sea, and shipping lanes in the main harbors have been deepened many meters by dredging. During the last 25 years, the situation has, however, begun to improve with a reduction in pollution, and the tenets of environmental awareness have become engrained within society. With improvements in water quality, the first recoveries of aquatic plants and benthic fauna have been reported, and many city inhabitants on estuaries are able now to recreate in restored tidal freshwater marshes (Baldwin 2004).

Physical and Chemical Processes

Water is the medium of transport and determinant of most chemical and physical conditions in tidal freshwater wetlands. Hydrology in estuaries is complex. The diurnal tides cause enormous flows in water with sometimes extreme current. Normal tidal amplitude in wetlands bordering oceans ranges from 1 to 2.5 m, with exceptions up to 6 m in funnel-shaped estuaries. This amplitude is the same in the freshwater sections, but the amplitude will decrease upstream in the river. On average the tidal wave comes 40–200 km inland from the sea, depending on the dimensions of the estuary and the river. The tidal amplitude differs by tide due to the neap and spring tidal cycle and is also affected by the quantity of discharge from the river. The ebbing period is longer than the flood period in the freshwater section of the estuary, resulting in an asymmetrical tidal curve. Moreover, hydrology in the larger estuary is influenced by the rotation of the earth, creating the difference in the flood stream along one shore and the ebb stream along the other and forming banks and shoals in the middle of the channel. Due to high water velocity, these sedimentary banks and shoals are mostly composed of the heavier sand component; plant growth further reduces the current. This sand originates from the river basin; the sea is merely a sink.

The production of muddy sediments is prominent in the freshwater section of the estuary, and their development is the result of sedimentation of suspended material, exported from the river catchment, stimulated through a chemical process of flocculation. Tidal movements create an interface without current between the heavier saline water in the deeper channels and the fresh river water flowing to the sea above it. At this interface, ions from the saline water start to attract organic ions from the river water, resulting in large flocs that will settle and accumulate at locations without current. A second process is that diatoms in the water are the starting points to flocculate suspended matter. This sedimentation creates tidal mud flats and later, after accumulation, in accretion in tidal marshes. Production of marsh vegetation adds many roots and litter to this mud and produces a soil rich in organic matter.

One of the major ecosystem services of these tidal freshwater marshes is wastewater treatment – input of polluted river water from upstream and the export of purified surface water from the marshes into the brackish estuary. Many nutrients and metals are bound to and accumulate with the suspended matter, e.g., phosphates binding with iron and calcium and fixation of nitrogen to organic matter. Heavy metals and pesticides can be stored during the same process. Silica is also recycled in these wetlands (Struyf et al. 2005).

Organic matter in wastewater discharged into the river is greatly reduced and disappears from the system as atmospheric CO_2. As a result of diurnal fluctuations in the water table, the intertidal system is high in oxygen at low tide but poor in oxygen at high tide with flooding. These fluctuations stimulate nitrification and denitrification of the nitrogen, finally ending in the discharge of atmospheric N_2. The reduction of organic waste and the change in nitrogen status are chemical processes performed by bacteria. Permanent wet soil with the groundwater level always at the soil surface results in non-oxide conditions with only the first millimeters with oxygen. This condition does not fluctuate seasonally as with other wetlands and is characteristic of tidal freshwater wetlands as result of a constant sea level, regular flooding of the marshes and swamps, and resistance of clay soils to water flow. The reduction of organic matter under reduced but fresh conditions takes place with the process of methanogenesis (Weston et al. 2011).

In summary, compared to other wetland types, the processes within tidal freshwater wetlands are very fast in terms of hydrological disturbance, sedimentation, and chemical or biological processes. However, at the same time, permanent high water tables in the marshes characterize the system, indicating an ecosystem with permanent oxygen-poor conditions. Another characteristic is that the system is eutrophic, and high nutrient concentrations can be reduced through both chemical and biological processes. The plant and animal species that are present can survive the flooding stress and the high nutrient levels.

Flora

There is a distinct zonation in the vegetation, linked to the flooding frequency explained by the elevation of the location and the flooding levels. This variation in subsystems perpendicular to the shoreline in the gradient from the tidal channel to the upper terrestrial parts is reported from North and South America and Europe. Although the species might be different for each area, the morphology remains comparable (Fig. 3). Aquatic plants are not common in tidal creeks as water current and turbidity prevents their establishment and development. Only in parts isolated from these pressures can aquatic plants develop. The mud flats flooded for longer than half of the tide are too dynamic and unconsolidated to allow plant growth.

Vegetation in the low marsh gradient can survive and grow although experiencing flooding for many hours because of aerenchymous tissues in stems; rhizomes transport oxygen below the water surface. In Europe and South America these might be species from the genus *Schoenoplectus*, and in North America some prominent species are *Nuphar lutea*, *Peltandra virginica*, and *Pontederia cordata*. Many helophytes are found in a somewhat higher elevated but still frequently flooded zone. In Europe some dominant species are *Phragmites australis*, *Typha angustifolia*, and *T. latifolia*; many herbs also occur. In North America the same *Typha* species are present as well as *Zizania aquatica* but these can be replaced to the south by *Zizaniopsis miliacea* and *Cladium mariscus*. Many other herbs and grasses can be added to this zone. In South America the species *Zizaniopsis bonariensis* and *Panicum grumosum* are represented.

The high marsh is represented where normal flooding is present for only a shorter period each day, but the groundwater table is still almost at the surface. In North America this vegetation has an extremely high diversity with many species of *Polygonum* and *Bidens*; in Europe it is mostly *Phragmites* with many herbs, e.g.,

Fig. 3 Tidal freshwater wetlands in the Netherlands (Oude Maas) with sequence showing zonation with increasing elevation – *Schoenoplectus* sp., *Phragmites* sp., and *Salix* sp. at high tide level (Photo credit: A. Barendregt © copyright remains with the author)

Symphytum officinale, and frequent vines. In South America *Schoenoplectus giganteus* and *Eupatorium tremulum* dominate in these marshes. In these same high-marsh locations, a swamp can also develop with many species such as *Cephalanthus occidentalis* in the northern USA and *Taxodium distichum* more to the south. In Europe many *Salix* species are present and in South America *Erythrina crista-galli* can dominate. Higher in the gradient, the flooding will be restricted to storm tides and in most cases there is a riparian forest.

Many wetland species are typical and widespread but locally some rare or threatened species are linked to tidal freshwater wetlands. They all have in common the ability to withstand flooding and the shortage in soil oxygen. Many wetland species are typically perennial. In Europe almost all species are perennial; in North America some annual species (e.g., *Zizania* and *Polygonum*) are also well represented. Research indicated that the seeds of many plants are transported by water (buoyancy), creating optimal conditions for distribution in flooding areas, although seeds of some other species (e.g., *Zizania*) fall directly from the parent plant on the soil. Just by the dynamics in the tidal wetlands, the seed banks appeared to be very rich in species, but not all species can germinate in the tidal conditions. Some species are invasive in the wetlands, with local impact on native biodiversity. In North America the problem is mainly by *Phragmites australis*; in Europe this might be with *Impatiens glandulifera*.

The tidal freshwater subsystems in all continents have in common that the yearly production in aboveground biomass is very high compared to other systems. The belowground biomass is also high (comparable with aboveground) as can be expected from vegetation with many perennial species. An aboveground production of 10–20 ton/ha/year appears to be normal and extremes up to 40 ton are reported. This level of production is not unexpected in a system with abundant and ever-present water, rich in nutrients. However, a 5-year study on effects of nutrient additions indicated that nitrogen might be limiting production (Ket et al. 2011). Other research indicated plants, especially annual species, responded positively to the addition of nitrogen. On marshes where flooding with nutrient-rich river water is present on a diurnal basis, the limitation in nutrients might, however, be of minor value compared to the stress from flooding with absence of oxygen in the soil. However, most species have a specialized root system to survive this stress.

Fauna

The faunal diversity of tidal freshwater wetlands is not extremely high, but the diversity in subsystems creates niches for many species. Compared to plants, the aquatic component is important for the fauna, the water itself (pelagic) and the soil underwater (benthic). For pelagic fish species, tidal freshwater wetlands are really an interface between the saline sea and freshwater rivers. Most inland (river) species are present in the fresh part of the estuary in addition to species from the brackish estuary entering the freshwater parts, thereby increasing the species diversity. Diadromous fish species use the gradient in salinity associated with freshwater tidal wetland habitat during their migration to and from the sea to adjust their physiological (salinity) equilibrium. A well-known example is the salmon, but many other species can be mentioned, e.g., the American shad *Alosa sapidissima* in North America and the twaite shad *A. fallax* in Europe.

Many fish species feed on invertebrates, e.g., zooplankton that in turn feed on phytoplankton. The tidal freshwater habitat is rich in both; diatoms are especially important to the food web. Crustaceans (amphipods), copepods, and insects (chironomids) together with the frequent oligochaetes (tubificids, naidids) are the most important faunal groups in the subtidal habitats with densities typically 10,000 individuals/m^2. These groups of species are also present in the intertidal habitat (mud flats, low marsh) of the tidal freshwater wetlands. Mollusks are present with many snail and bivalve species (sphaeriids and unionids).

Many of these species (especially tubificids and chironomids) are also represented in the elevated marshes and swamps; and many insects can survive the flooding conditions. Terrestrial gastropods, beetles, spiders, and springtails (Collembola) are important groups in biomass and quantities. Due to the irregular flooding frequency, aquatic species can be present just above mean high tide level and at the interface between water and land; only a select (characteristic) series of invertebrate species prefer this zone. Most terrestrial invertebrates behave optimally far above mean high tide level although depending on a species' tolerance they can be present closer to the tidal flooding zone.

European tidal wetlands are generally poor in amphibians and reptiles, whereas the freshwater section in North American estuaries is comparatively rich. Frogs and toads are frequent and turtles and snakes are not uncommon. Small mammals (mice, shrews) are frequent in both continents in the higher elevated marshes and swamps. Diversity in larger mammals is higher in North America, e.g., with many beaver *Castor canadensis*, muskrat *Ondatra zibethicus*, and otter *Lontra canadensis*.

Bird abundance and diversity is high in tidal freshwater wetlands, in both Europe and North America, although species differ. Food that includes seeds, insects, and small fishes is abundant in the wetlands and contributes to this bird abundance; the wetlands provide habitat for many specialized bird species. European reed marshes, swamps, or tidal forests are especially important, whereas in North America the high marshes and swamps contain the highest diversity of species. Waterfowl (from ducks to rails) find optimal conditions in the flooding zones. The diversity and close juxtaposition of the subsystems provide especially favorable conditions for nesting. The high abundance of fish species creates fine conditions for bitterns and herons to forage and nest. Raptors such as the osprey *Pandion haliaetus* in North America and the European hen harrier *Circus cyaneus* can be common locally. Many non-nesting birds use the wetlands during the migration period or in winter to find food. Benthivorous waders and many duck species that feed on small invertebrates (e.g., northern shoveler *Anas clypeata*) are frequent in this ecosystem. Due to the current in channels, the water is seldom frozen in winter which offers great opportunities for migrating waterfowl.

Threats and Future Challenges

Ecosystem services have been receiving more societal attention in North America and Europe in recent years. The prominent role that the tidal wetlands have in recycling of water with the reduction of nutrients and organic waste is no longer neglected. Another consideration is tidal wetlands can prevent or reduce economic damage from flooding by storing a great quantity of storm water. There are examples (e.g., close to Antwerp, Meire and Van Damme 2005) where tidal freshwater wetlands are installed for these ecosystem service benefits. Because tidal wetlands are typically close to cities, many people wish to avail themselves of the recreational opportunities these wetlands can provide, e.g., walking trails that incorporate education.

Experience from North America and Europe with the restoration of tidal freshwater wetlands indicates that there are few problems to restoring the system. Excavation, creation of new creeks, and storage of dredged sediment are elements of the activities. In the USA restoration often involves the planting of the desired species, while in Europe the general policy is species will migrate from surrounding tidal areas and species presence will be a response to the harsh flooding conditions. Monitoring of restoration projects has informed that early colonizing species dominate in the initial years but typical tidal freshwater species become established and dominate after a decade. The physical processes with sedimentation and natural vegetation growth are quickly reestablished due to the dynamic flooding system rich with sediments and nutrients.

Global Warming and Sea Level Rise

During the last millenniums, estuaries have continuously changed as a result of sea level rise, but present predictions indicate a more rapid change that might impact the otherwise robust system of tidal freshwater wetlands. A number of interlinked factors might result in changes to water levels, river discharge, and salinity.

The rising water table in the sea will affect shorelines and flood tidal freshwater wetlands more frequently. However, the freshwater section is very rich in sediments and impacts may be limited if accretion is able to keep pace with sea level rise. This process was probably present during former rises in sea level. The vertical accretion currently varies in time and space; and within hundreds of meters, sedimentation can range from 0 to 40 mm/year (Neubauer 2008). Partial loss of the accretion occurs during the winter period when vegetation is absent. A potential response to sea level rise is geographical migration of tidal freshwater wetlands upstream into the river valley. This migration will be affected by a couple of factors. Estuaries are typically funnel shaped and less space is available for wetland migration upstream into the river; and the area upstream is in most cases already occupied with housing and industry, and for economic reasons unavailable for wetland establishment.

Climate change might result in drier summer periods and less river discharge into the estuary. The consequence will be that freshwater input will be reduced and the level in the river decreases. Because the sea level is maintained, brackish water can flow further upstream. This will affect the tidal freshwater wetlands in its most vulnerable aspect, the freshwater component. Increased salinity will impact plant and animal species; many of which cannot tolerate the pulses in salinity and thus changing the competition equilibriums in species composition from a fresh to a brackish marsh. Far more significant are the impacts of salinity on the biogeochemical processes (Weston et al. 2011; Jun et al. 2013). The mineralization of organic matter in the fresh wetlands through methanogenesis will be replaced by a more efficient sulfate reduction with sulfur from brackish water. Saltwater intrusion stimulates the microbial mineralization of organic matter. As the soil in the marshes consists of clay and organic matter (in high marshes more than 50 % organic matter), the marshes will shrink and will be flooded more frequently. At the same time, the storage of carbon will be disturbed and emission of CO_2 into the atmosphere will be stimulated.

Cross-References

► Estuaries
► Tidal Salt Marsh

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