Appendix A: Natural System Processes and Interactions

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Understanding the natural processes as well as the economic and social services or functions that rivers, lakes, reservoirs, wetlands, estuaries and coasts fulfill is critical to the successful and sustainable management of these hydrological systems. These natural processes involve numerous physical and biological interactions that take place among the components of fluvial systems and their adjacent lands. This appendix briefly views some of the important natural processes and interactions that occur in watersheds, river basins, estuaries and coasts. Those who manage them should be aware of these processes and interactions as they build and use their models to analyse, plan and evaluate alternative management policies and practices.

1. Introduction

The hydrological, geomorphological, environmental and ecological state of streams and rivers, and of their downsteam estuaries and coasts, are indicators of past and current management policies or practices. The condition of a stream, river, estuary or coast is an indicator of how well it, as a system, can function. Natural systems can filter contaminants from runoff; store, absorb and gradually release floodwaters; serve as habitat for fish and wildlife; recharge groundwater; provide for commercial transport of cargo; become sites for hydropower; and provide recreational opportunities beneficial to humans. Degraded systems do not perform these functions as well as non-degraded systems.

Today the importance of keeping natural aquatic systems alive and well, diverse and productive, in addition to meeting the needs of multiple economic and social interests, is much better appreciated and recognized than it was when water resources planners and managers were involved in 'conquering nature and taming its variabilities'. Natural system restoration and sustainability have become major management objectives, along with the maintenance of the usual economic services that water and related land management can provide. Satisfying all these objectives as far as possible requires an understanding of the basic hydrological, geological, environmental and ecological interactions that take place in natural aquatic systems.

This appendix is divided into five main sections. The next section will focus on rivers. It is followed by sections describing lakes and reservoirs, wetlands, estuaries, and finally coasts. Multiple books have been written on each of these water resources system components. What is presented in this appendix is thus only an outline of the main features of these water bodies and how they can be managed. Its purpose is to introduce some vocabulary and serve as a primer for those not familiar with this background information.

2. Rivers

Rivers are driven by hydrological, fluvial, geomorphologic, water quality and ecological processes that occur over a range of temporal and spatial scales. The plant and animal communities in rivers and their floodplains are dependent upon change: changing flows, moving sediments and

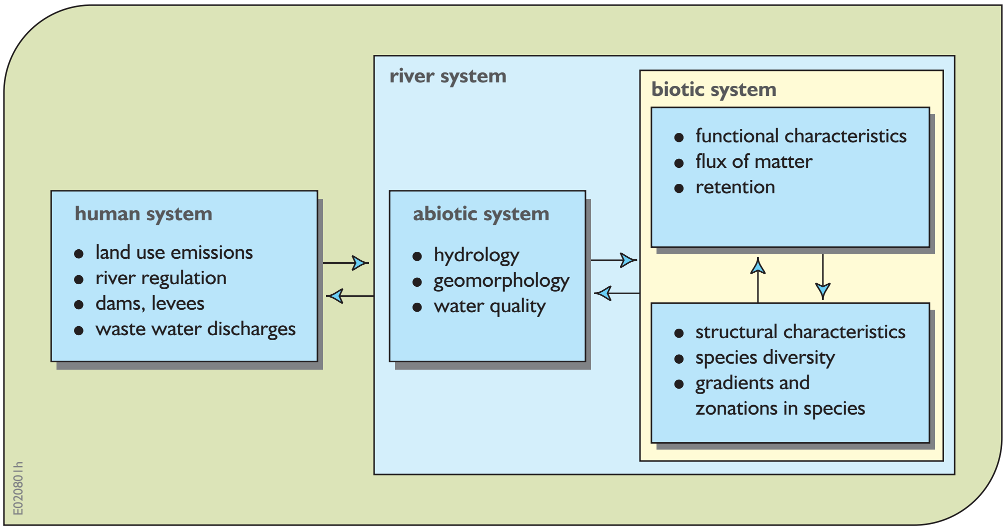

Figure A.1. Cause and effect chain of factors influencing a river system.

shifting channels. They depend on inputs of organic matter from vegetation in the riparian zone. They depend on the exchange of nutrients, minerals, organic matter and organisms between the river and its floodplain. This is provided by variable flows and sediment transport. All of these factors influence the structural character of the stream or river and its aquatic and terrestrial ecosystems – their species distribution, diversity and abundance.

Assessments of the effect of human activities on river systems require indicators relating cause to effect. A cause–effect chain is illustrated in Figure A.1. Insight into connections between processes and structures and their temporal and spatial scales leads to a more integrated interdisciplinary approach to river system monitoring and management.

2.1. River Corridor

A river corridor can be viewed as a hierarchical series of river segments, from upstream headwater streams to large downstream rivers, as illustrated in Figure A.2. River corridors include the river channels and the river margins (the water–land interfaces), and both are influenced by surface water–groundwater interactions. These environments are characterized by hydrological, geomorphological, environmental and ecological interactions. River margin interactions influence surrounding terrestrial landscapes.

Features that influence the structure and functioning of river systems occur at various spatial scales. A stream or river, for example, has an input–output relationship with the next higher scale, the stream or river corridor. This corridor scale, in turn, interacts with the landscape scale, and so on up the hierarchy. Similarly, because each larger-scale system contains the smaller scale ones, the structure and functions of the smaller systems affect the structure and functions of the larger.

Investigating relationships between structure and scale is a key first step for planning and designing stream or river system management plans. Landscape ecologists use four basic terms to define spatial structure at a particular scale.

These spatial landscape, component types in river basins, illustrated in Figure A.3 are:

- *Matrix*. The dominant and interconnected land cover in the basin.
- *Patch*. A different type of land cover found on smaller areas within the matrix.
- *Corridor*. A land cover type that links other patches in the matrix. Typically, a corridor is elongated in shape, such as a stream or river.
- *Mosaic*. A collection of isolated patches.

The 'watershed scale' that includes the stream corridor is a common scale of management, since many functions of the stream corridor are closely tied to drainage patterns. While the watershed scale is often the focus of river restoration and water resources management, especially for non-point pollutant discharge management, the other spatial scales should also be considered when developing a stream or river system management policy or plan. The

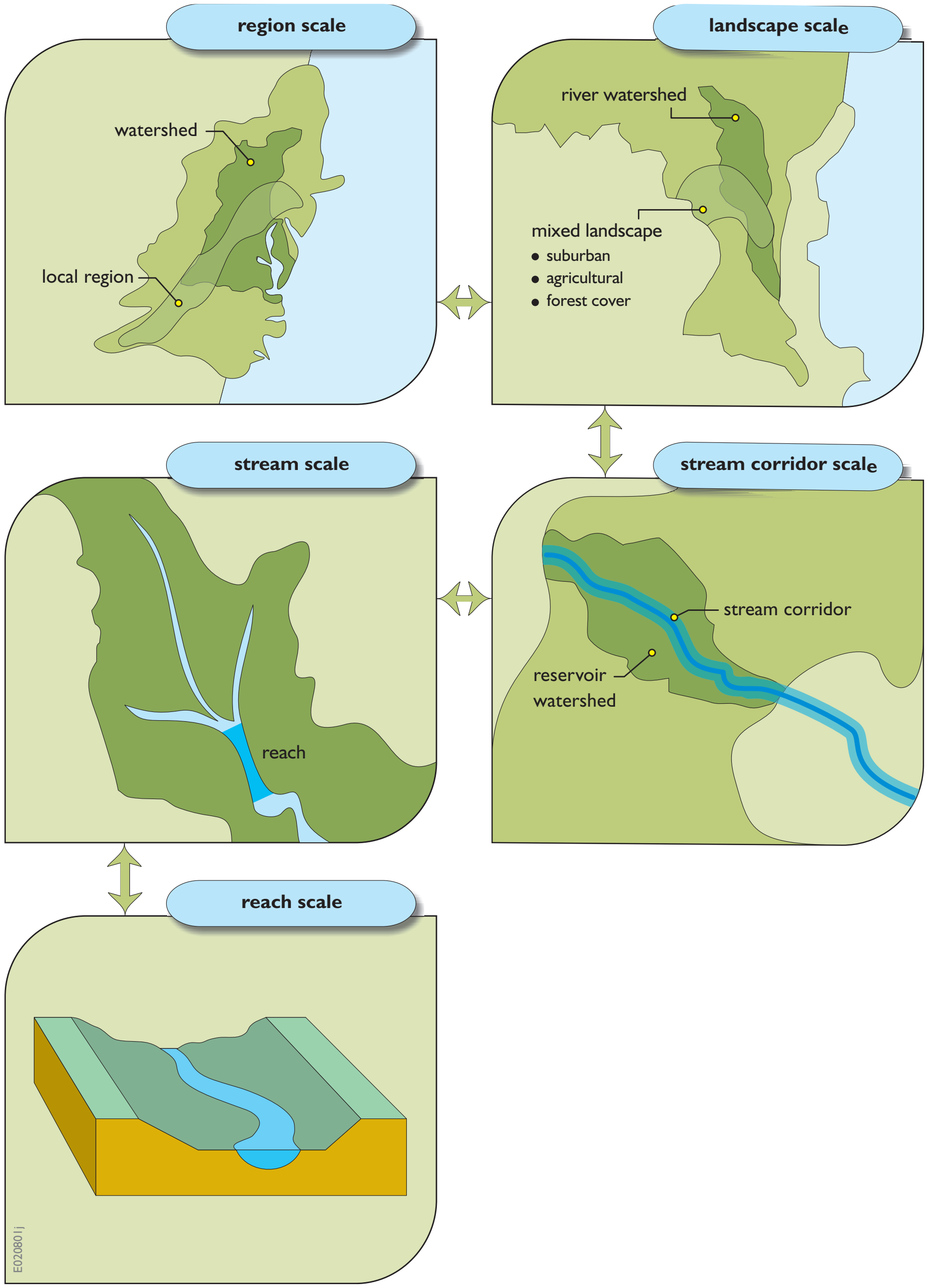

Figure A.2. River basin components viewed at multiple spatial scales, from the large regional scale to the local stream segment scale.

exclusive use of watersheds for the large-scale management of stream corridors, however, ignores the materials, energy and organisms that move across and through landscapes independent of water drainage. A more complete large-scale perspective of the stream and river system management is achieved when watershed hydrology is combined with landscape ecology and when actions in 'problem sheds' rather than only in drainage basins are being considered.

2.1.1. Stream Channel Structure Equilibrium

Nearly all channels are formed, maintained and altered by flows and sediment loads. Channel equilibrium involves the relation among four basic factors: sediment discharge, Q_s; sediment particle size, D; streamflow, Q_w; and stream slope, S. Lane (1955), using median particle size, D_{50}, expressed this relationship qualitatively as:

$$Q_s \cdot D_{50} \propto Q_w \cdot S \qquad (A.1)$$

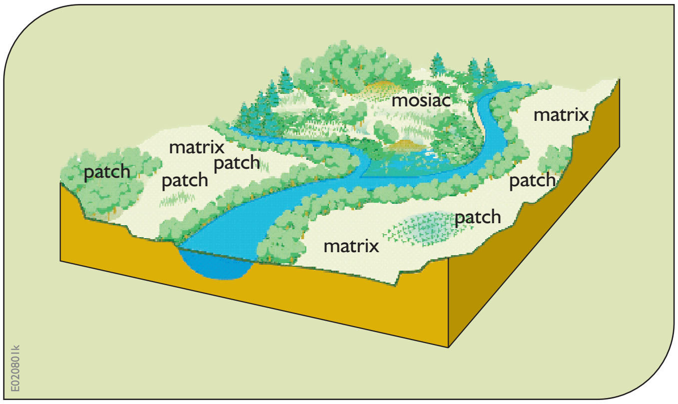

Figure A.3. River basin landscapes made up of matrix, patch, corridor and mosaic components at various scales.

This relationship states that a measure of sediment load (sediment discharge Q_s times median particle size D_{50}) is proportional to a measure of the streamflow power (streamflow Q_w times slope S). Channel equilibrium occurs when the streamflow power is constant over the length of the stream. If this occurs, no net changes in the channel shape will occur. If a change occurs in either the left or right-hand side of Equation A.1, the balance and hence equilibrium will be temporarily lost. If one variable changes, one or more of the other variables must change appropriately if equilibrium is to be maintained. Reaching equilibrium typically involves erosion and/or deposition.

Assuming increasing flows from runoff in the downstream direction, the channel slope has to be decreasing in the downstream direction. If the slope is too steep, sediment is deposited to reduce that steepness. This is why stream channels that experience increasing downstream flows have decreasing slopes in the downstream direction.

If streams in equilibrium have constant streamflow power, Q_wS, over distance, from Equation A.1, the sediment load, Q_sD_{50}, must also be constant. Hence, if sediment deposition is occurring in the downstream direction to decrease stream slopes, the median particle size, D_{50}, will be decreasing and the sediment discharge, Q_s, along with streamflow, Q_w, will be increasing. This is typically observed in channels with increasing downstream streamflows.

A stream seeking a new equilibrium tends to erode more sediment and larger particle sizes. Alluvial streams that are free to adjust to changes in these four variables generally do so and re-establish new equilibrium conditions. Non-alluvial streams such as those flowing over bedrock or in artificial, concrete channels are unable to maintain this equilibrium relationship because of their inability to pick up additional sediment.

The stream balance expressed in Equation A.1 can be used to make qualitative predictions about the impacts of changes in runoff or sediment loads from a watershed. Quantitative predictions, however, require the use of more complex simulation or physical models.

2.1.2. Lateral Structure of Stream or River Corridors

Stream and river valleys are created over time by the stream or river depositing sediment as it moves back and forth across the valley floor. These processes of lateral migration and sediment deposition, usually occurring during flood flows, continually modify the floodplain. Through time, as the channel migrates, it will maintain the same average size and shape as long as the channel stays in equilibrium.

One can distinguish two types of floodplains. The hydrological floodplain is the land adjacent to the baseflow channel residing below bank-full elevation. It is inundated about two years out of three. Not every stream corridor has a hydrological floodplain. The topographic floodplain is the land adjacent to the channel, including the hydrological floodplain, that is flooded by a flood peak of a given frequency (for example, the 100-year flood – the flood that is equalled or exceeded once every 100 years on average – defines the 100-year floodplain). Higher flood-peak flow return periods define wider topographic floodplains. These two types of floodplains are shown in Figure A.4.

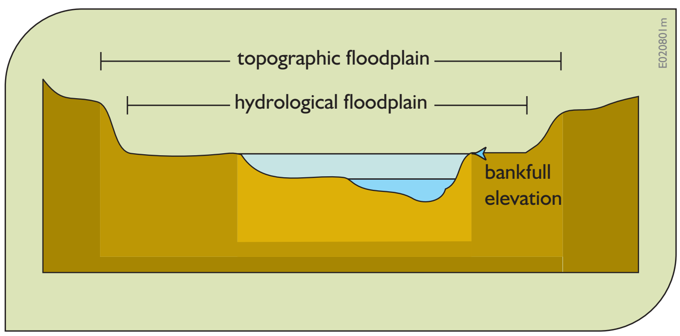

Figure A.4. Two types of floodplains, the hydrological and topographic.

Floodplains provide temporary storage space for floodwaters and sediment. This lengthens the lag time of a flood. This lag time is the time between the middle of the rainfall event and the runoff peak. If a stream's capacity for moving water and sediment is diminished, or if the sediment loads become too great for the stream to transport, the valley floor will begin to fill.

Topographic features on the floodplain, as illustrated in Figure A.5, include:

- *Meander scroll*. A sediment formation marking former channel locations.
- *Chute*. A new channel formed across the base of a meander. As it grows in size, it carries more of the flow.
- *Oxbow*. A severed meander after a chute is formed.
- *Clay plug*. A soil deposit at the intersection of an oxbow and the new main channel.
- *Oxbow lake*. A water body created after clay plugs separate the oxbow from the main channel.
- *Natural levees*. Formations built up along the bank of some streams that flood. As sediment-laden water spills over the bank, the sudden loss of depth and velocity causes coarser-sized sediment to drop out of suspension and collect along the edge of the stream.
- *Splays*. Delta-shaped deposits of coarser sediments that occur when a natural levee is breached. Natural levees and splays can prevent floodwaters from returning to the channel when floodwaters recede.
- *Backswamps*. A term used to describe floodplain wetlands formed by natural levees.

These different features provide a variety of habitats for plants and animals.

2.1.3. Longitudinal Structure of Stream or River Corridors

The processes that determine the characteristic lateral structure of a stream corridor also influence its longitudinal structure. For streams and rivers whose flows increase with distance downstream, channel width and depth also increase downstream due to increasing drainage area and discharge. Even among different types of streams, a common sequence of structural changes, as shown in Figure A.6, is observable from headwaters to mouth.

The longitudinal profile of many streams can be divided into three zones. The changes in the three zones are characterized in Figure A.6. Zone 1, the headwater zone, has the steepest slopes. In this zone sediments erode from slopes of the watershed and move downstream. The rivers in hilly regions are characterized by the swiftness of the flow in restricted and/or steep channels, the occurrence of landslides and the formation of rapids along their courses. The control of rivers in the upper reaches is known as 'torrent control'. Zone 2, the transfer zone, receives some of these sediments and hence is usually characterized by wider floodplains and more meandering channel patterns. The flatter slopes in zone 3 receive most of the coarser sediments. 'River training' methods are often adopted for managing alluvial rivers in this most downstream zone.

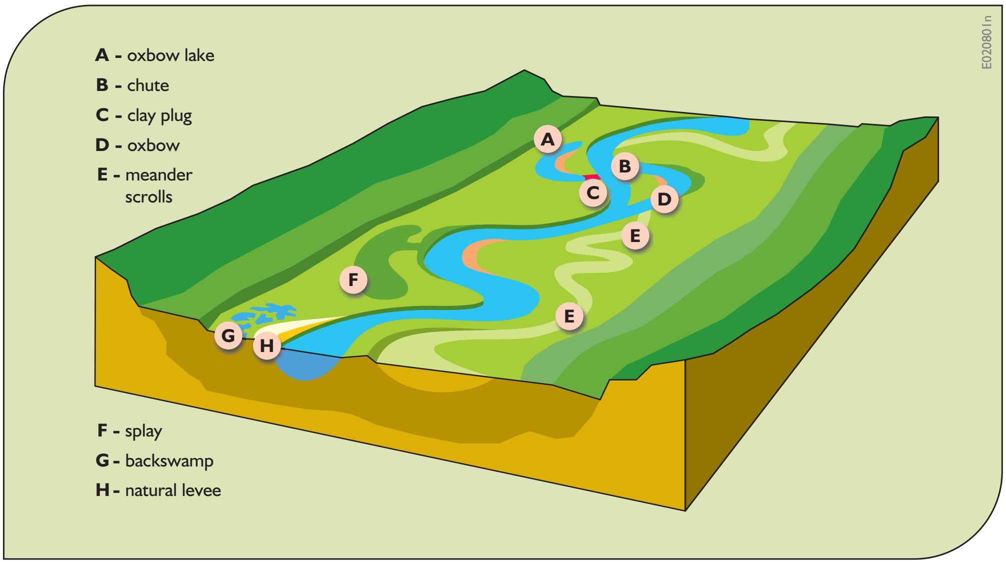

Figure A.5. Topographic features of a meandering stream on a floodplain.

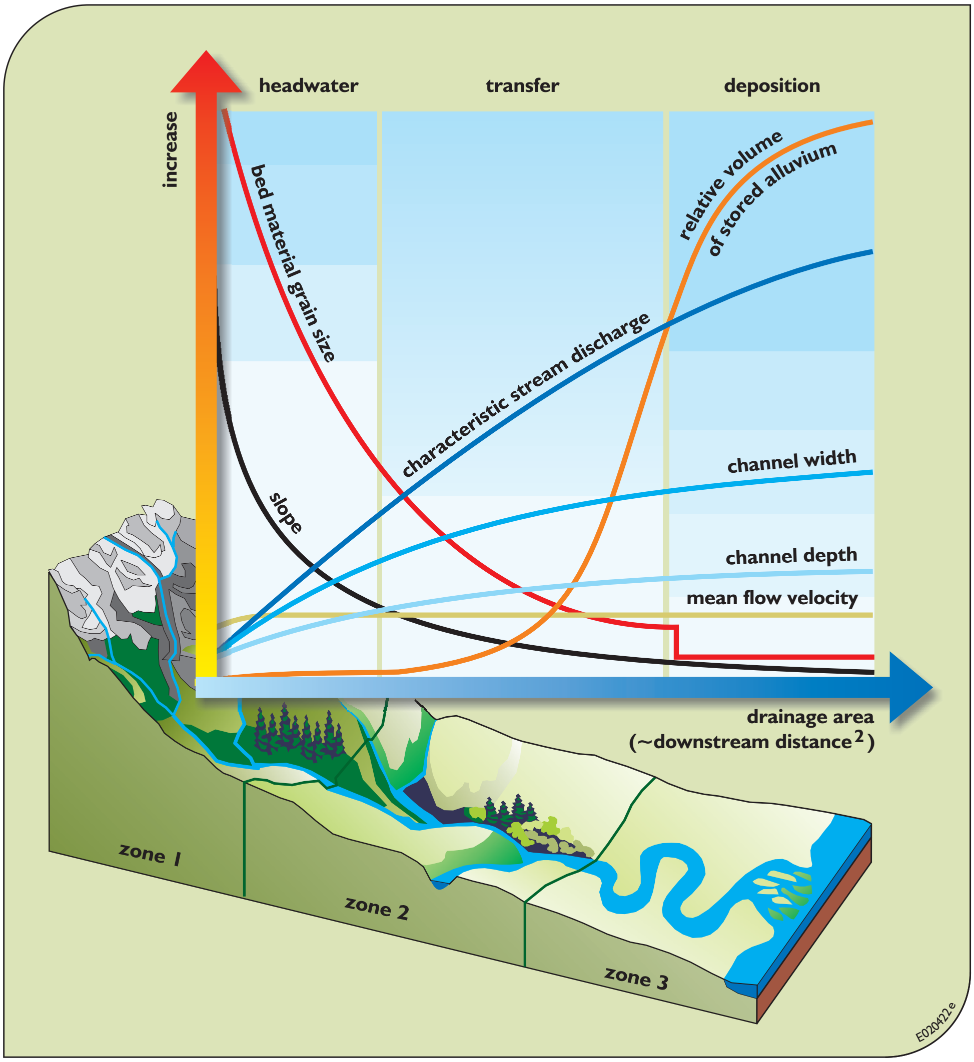

Figure A.6. Typical changes in the stream channel characteristics along its length.

Though Figure A.6 displays headwaters as mountain streams, these general patterns and changes apply to watersheds with relatively small topographic relief from the headwaters to the mouth. Erosion and deposition occur in all zones, but the zone concept focuses on the most dominant process.

2.2. Drainage Patterns

One distinctive aspect of a watershed or river basin when observed from above (bird's-eye view) is its drainage pattern. Drainage patterns are primarily controlled by topography and geologic structure. Figure A.7 shows a method of classifying, or ordering, the hierarchy of natural channels within a watershed or basin. This is a modified method based on the one proposed by Horton (1945).

The uppermost channels in a drainage network (headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence. A second-order stream is formed below the confluence of two first-order channels. Third-order streams are created when two second-order channels join, and so on. The intersection of a channel with another channel of lower order does not raise the order of the stream below the intersection, e.g. a fourth-order stream intersecting with, a second-order stream is still a fourth-order stream below the intersection.

Within a given drainage basin, stream order correlates well with other basin parameters, such as drainage area or channel length. Consequently, knowing what order a stream is can provide clues to other characteristics, such as its longitudinal zone and its relative channel size and depth.

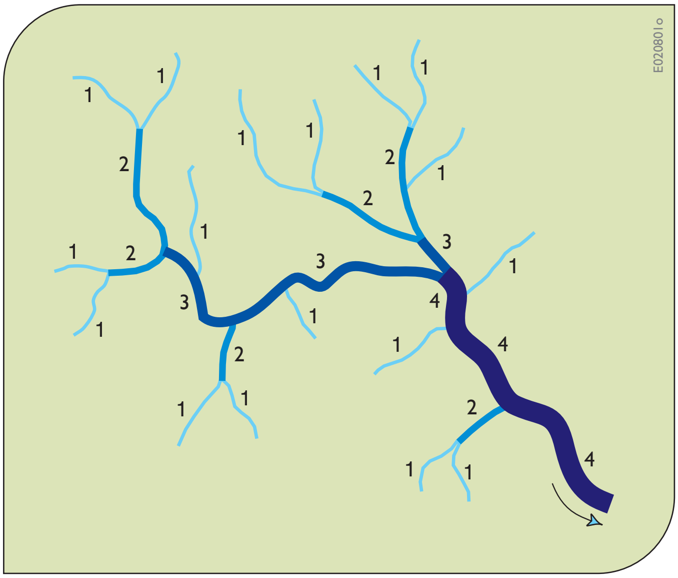

Figure A.7. Stream ordering in a drainage network showing first-order streams down to fourth-order streams.

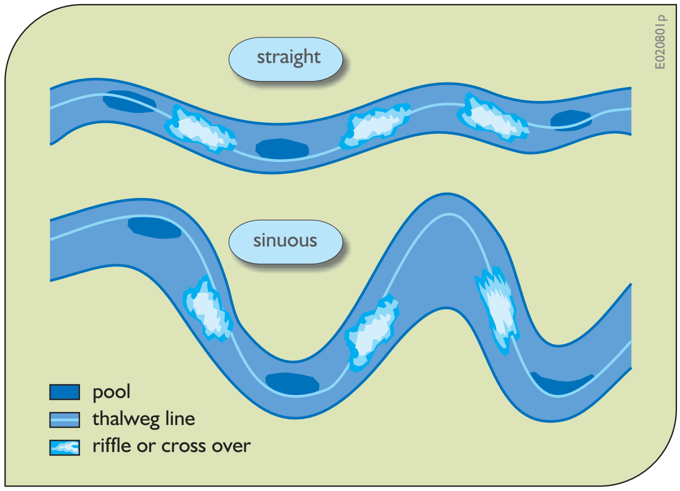

Figure A.8. Sequence of pools and riffles in straight and sinuous streams.

2.2.1. Sinuosity

Sinuosity (Figure A.8) is a term indicating the amount of curvature in the channel. The *sinuosity* of a reach is its channel centreline length divided by the length of the valley centreline. If the channel-length/valley-length ratio is more than about 1.4, the stream can be considered meandering in form. Sinuosity is generally related to streamflow power (slope times flow). Low to moderate levels of sinuosity are typically found in zones 1 and 2 of the longitudinal profile (Figure A.6). Sinuous streams often occur in the broad, flat valleys of zone 3.

2.2.2. Pools and Riffles

Most streams share a similar attribute of alternating, regularly spaced, deep and shallow areas called *pools* and *riffles* (Figure A.8). Pools and riffles are associated with the deepest path along the channel (thalweg). This deepest path meanders within the channel. Pools typically form in the thalweg near the outside bank of bends. Riffle areas usually form between two bends at the point where the thalweg crosses over from one side of the channel to the other. The pool-to-pool or riffle-to-riffle spacing, where they exist, is normally about five to seven times the channel width at bank-full discharge (Leopold et al., 1964).

2.3. Vegetation in the Stream and River Corridors

Vegetation typically varies along and across stream and river corridors. In zone 1, flood-dependent or tolerant plant communities tend to be limited but provide vegetative organic matter along with the sediment to zones 2 and 3 downstream. Woody debris from headwaters forests can be among the important features supporting food chains and instream ecological habitats in rivers (Maser and Sedell, 1994).

Zone 2 is typically a wider and more complex floodplain and larger channel than zone 1. The lower gradient, larger stream size and less steep terrain in zone 2 often allow more agricultural or residential development. This development may restrict the diversity of the natural plant communities in the middle and lower reaches, especially when land uses involve clearing and narrowing the corridor. Such actions alter stream processes involving flooding, erosion/deposition, and import or export of organic matter and sediment. This affects stream corridor geomorphology, habitat diversity, and water quantity and quality regimes.

The lower gradient, increased sediment deposition, broader floodplains and greater water volume in zone 3 typically lead to different plant communities than those found in the upstream zones. Large floodplain wetlands can develop on the flatter terrain.

The changing sequence of plant communities along streams from source to mouth is an important source of ecosystem resiliency. A continuous corridor of native plant communities is desirable. Restoring vegetative connectivity in even a portion of a stream will usually improve conditions and enhance the ecosystem's beneficial functions.

2.4. The River Continuum Concept

The river continuum concept identifies biological connections between the watershed, floodplain and perennial stream systems, and offers an explanation of how biological communities develop and change along perennial stream or river corridors. The concept is only a hypothesis, yet it has served as a useful conceptual model for describing some of the important features of perennial streams and rivers.

The river continuum concept assumes that, because of forest shading in many first to third-order headwater streams, the growth of algae, periphyton and other aquatic plants is limited. Since energy cannot be created through photosynthesis (autotrophic production), aquatic organisms in these lower order streams depend on materials coming from outside the channel such as leaves and twigs. Consequently, these headwater streams are considered *heterotrophic* (that is, dependent on the energy produced in the surrounding watershed). The relatively constant temperature regimes of these streams tend to limit biological species diversity.

Proceeding downstream to fourth, fifth and sixth-order streams, the channel widens, which increases the amount of incident sunlight and average temperatures. Primary production increases as a response. This shifts many stream organisms to internal autotrophic production and a dependence on materials coming from inside the channel (Minshall et al., 1985). Species richness of the invertebrate community increases due to the increase in the variety of habitats and food resources. Invertebrate functional groups, such as the grazers and collectors, increase as they adapt to both out-of-channel and in-channel sources of food.

Mid-ordered streams also experience increasing temperature fluctuations. This tends to further increase biotic diversity. Larger streams and rivers of seventh to twelfth order tend to increase in physical stability, but undergo significant changes in structure and biological function. Larger streams develop increased reliance on primary productivity by phytoplankton, but continue to receive heavy inputs of dissolved and fine organic particles from upstream.

Large streams frequently carry increased loads of clays and fine silts. These materials increase turbidity, decrease light penetration, and thus increase the significance of heterotrophic processes. The frequency and magnitude of temperature changes decrease as streamflows increase, and this in turn increases the overall physical stability of the stream as well as species competition and predation.

2.5. Ecological Impacts of Flow

Streamflow regimes have a major influence on the physical and biological processes that determine the structure and dynamics of stream ecosystems (Covich, 1993). High flows are important in terms of sediment transport. They also serve to reconnect floodplain wetlands to the channel. Floodplain wetlands provide habitat for aquatic plants as well as fish and waterfowl. Low flows promote fauna dispersment, thus spreading populations of species to a variety of locations. The life cycles of many riverine species require an array of different habitat types, whose temporal availability is determined by the variable flow regime. Adaptation to this environment allows riverine species to persist during periods of droughts and floods (Poff et al., 1997).

2.6. Geomorphology

The major large-scale physical characteristics of most streams and rivers have resulted from hydro-geological processes that have occurred over periods ranging from several decades to hundreds or even thousands of years. At smaller spatial scales, interactions between the hydrological cycle and the land that can alter the geometry of these water bodies take place in much shorter times, possibly ranging from a few minutes, hours or days to several years. Land use changes also influence the shape and flow directions of streams, rivers, estuaries and coastlines. Understanding how this happens requires a knowledge of how land cover and land-cover changes influence the partitioning of precipitation into runoff, infiltration, soil water storage, groundwater flow and storage, and discharge, and what impact all this has on the erosion, transport and deposition of sediment.

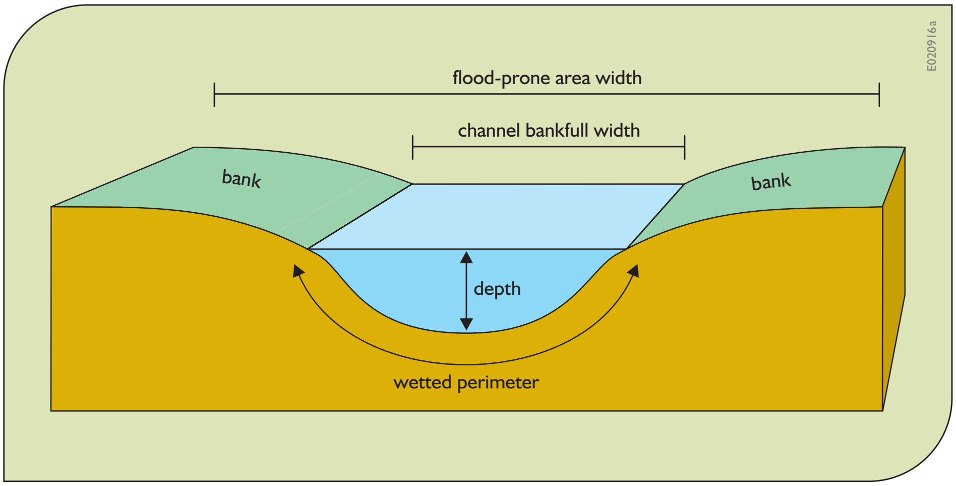

Figure A.9. Channel cross-section schematic.

2.6.1. Channel Classification

Streams and rivers are classified on the basis of their dimensions, configurations and shapes. Classifying channel morphology helps in the development of reproducible descriptions and assessments of channel flows, movement and sediment transport potential. Rosgen (1996) classified stream or river morphology based on bank-full width, channel sinuosity, slope and channel material size. While classifying a stream or river channel is helpful in understanding the behaviour of the channel and how the behaviour might change due to land use changes or modifications to the channel, it is only an aid in the management of a stream or river or in the development of an engineering design for its channel. Classification itself does not directly provide the detailed information needed for an engineering design solution.

The ratio of the flood-prone area width to the bank-full width is called the *entrenchment ratio*. The *width-to-depth ratio* is the ratio of the bank-full width to the mean bank-full depth. The *mean hydraulic depth* is the cross-sectional area (darker blue area marked as 'depth' in Figure A.9) divided by the wetted perimeter.

2.6.2. Channel Sediment Transport and Deposition

The energy contained in flowing water is typically expended by eroding and transporting sediment. The source of sediment comes in the runoff from the drainage area or from the channel bed and banks (Trimble and Crosson, 2000). The sediment transported in water can be dissolved, suspended and pushed along the bed by saltation and traction. The latter two processes form the bedload. Figure A.10 illustrates these types of sediment loads in a river channel.

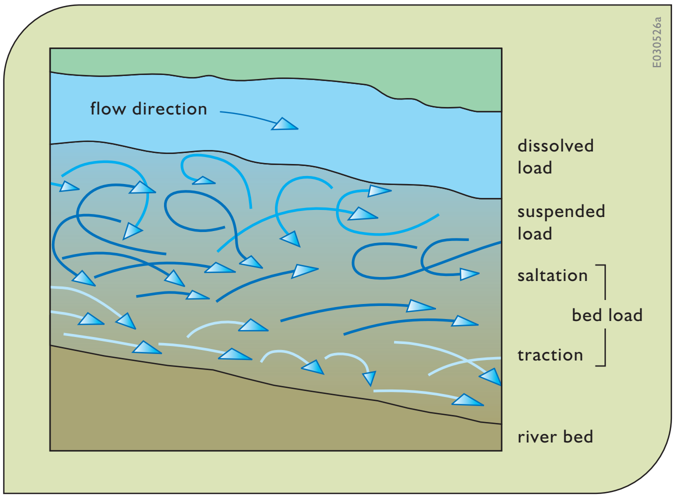

Figure A.10. Types of sediment loads in a river channel.

Sediments range from clays to gravel and, in extreme events, even boulders. They include clay (<0.004 mm), silt (0.004–0.062 mm), sand (0.062–1.000 mm), gravel (granules and pebbles, 1–64 mm), cobbles (64–250 mm), and boulders (>250 mm). Each of these size classes can be subdivided from fine to coarse. In addition, fine sediments can be cohesive (tending to attach to other sediments) or non-cohesive.

Energy is required to erode and transport sediment. The heavier the sediment particles, the more energy required to erode and transport them. The energy available to do this is a function of the rate of flow. Figure A.11

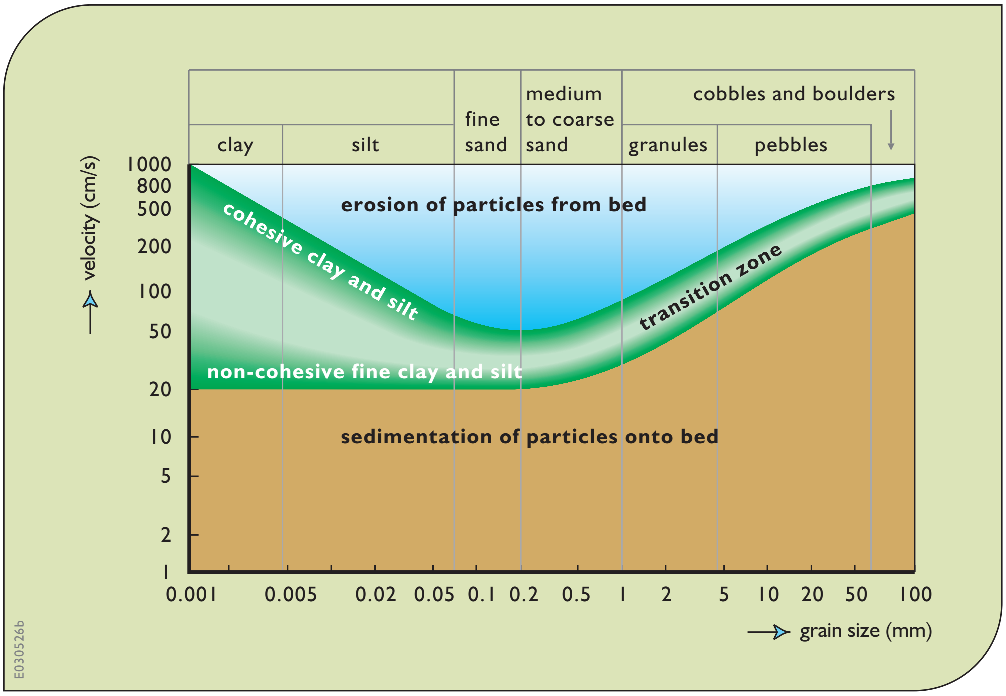

Figure A.11. Relation between flow rate and sediment particle size erosion and transport.

shows the approximate flow rates, in centimetres per second, needed to transport sediment particles of various sizes. Note that the ability to erode and transport cohesive fine sediments is much less than non-cohesive sediments.

If the energy of flowing water exceeds that needed to carry the existing sediment load, additional erosion can occur to add to the sediment load. Flowing water will seek to achieve its equilibrium sediment load. Conversely if the energy is insufficient to carry the existing load in the water, some of it will be deposited.

Considerable efforts have been made over the past decades to estimate, prevent and control soil erosion and sediment runoff from watersheds. To the extent that these prevention and control efforts have worked, increased stream channel and bank erosion have occurred. Controlling watershed erosion does not reduce the sediment carrying capacity of flows. If sediment is available in or on the banks of the stream or river channel, it will replace what otherwise might have come from watershed runoff. Especially in urbanizing watersheds, where watershed contributions to sediment loads have been substantially reduced, most of the total sediment yield can be due to channel and bank erosion.

Sediment is transported as bedload and/or as suspended load. The latter consists of fine materials such as clay, silt and fine sand that usually make the flow look muddy. Flows from snow or ice melt tend to carry fine particles of rock that can make the flow look emerald green. Lake Louise in Alberta, Canada is a classic example of this. If fine materials are available, the suspended load can be as high as 95% of the total sediment load carried by the stream or river flow. This fine material settles in areas of reduced velocity. Sediment deposition processes can eventually change the channel dimensions and even its location.

Bedload transport of coarser sediments involves a combination of sliding, rolling and saltation (bouncing). These transport processes begin when the flow velocity reaches a critical value for the particular size of the bed material. This critical velocity corresponds to a critical shear stress. The shear stress associated with a flow is an important parameter for sediment transport.

Suspended sediment particle settling (or fall) velocities influence the rate of deposition. These velocities are affected by particle shapes, the density or specific weight of the sediment particles relative to that of the water, and the chemical attraction (cohesion) of the particles, especially in clays. Equations have been proposed for estimating the terminal fall velocity of a single particle in quiescent, distilled water. While equations and graphs exist in handbooks for these and other individual particle size fall velocities under quiescent distilled conditions, measurements of fall velocities under natural conditions are much more reliable.

Erosion depends on *tractive stress* or *shear stress* that creates lift and drag forces at the soil surface boundaries in fields and along the bed and banks. Shear stress varies as a function of flow depth and slope. The larger the soil particle, the greater the amount of shear stress needed to dislodge and transport it downstream. The energy differential that sets sediment particles into motion is created by faster water flowing in the main body of the channel next to slower water flowing at the boundaries. The momentum of the faster water is transmitted to the slower boundary water. The resulting shear stress moves bed particles in a rolling motion in the direction of the current.

Sediment transport rates can be computed using various models, but the uncertainty associated with any sediment load prediction can be considerable. Predicting sediment transport is one of the most enduring challenges facing hydrologists and geomorphologists.

Stream channels and their floodplains are constantly adjusting to the water and sediment in them. Channel response to changes in water and sediment yield may occur at differing times and locations, requiring differing levels of energy. Daily changes in streamflow and sediment load result in frequent adjustment of bedforms and roughness in many streams with movable beds. Streams also adjust periodically to extreme high and low-flow events. Both flood and drought flows often remove vegetation as well as creating and increasing vegetative potential along stream and river corridors. Long-term adjustments in channel structure and vegetation may come from changes in runoff or sediment yield from natural causes, such as climate change or wildfire, or from human activities such as cultivation, overgrazing or rural-to-urban conversions. Changes in vegetation can also affect streamflow and sediment deposition. Bio-geomorphology is the term used for the study of these plant, soil and water interactions.

2.6.3. Channel Geometry

Like all physical systems, stream and river flows and their sediment loads will attempt to reach an equilibrium. The equilibrium between flows and sediment erosion, uptake and deposition, is sometimes referred to as *regime theory*. Leopold and Maddock (1953) derived regime relations in stream and river channels in alluvial (sedimentary) basins. These relations predicted the stream width, w; mean hydraulic depth, h; velocity, U; sediment concentration, Q_s; slope, S; and Manning's n friction coefficient as a power function of the discharge, Q, in the stream or river. Each of these relations i is of the form a_iQ^{bi}. Leopold and Maddock found the values of these different coefficients a_i and b_i for a variety of rivers in the United States (also in Richardson et al., 1990).

The values of the coefficients a_i and b_i may differ along the length of the stream or river (Leopold, 1994). In the downstream direction the relative change in the width will increase more rapidly than the relative change in velocity. Hence, the coefficients a_i and b_i associated with width, depth and velocity will change. However, since the product of width, depth and velocity equals the flow Q, and each equation a_iQ^{bi} for width, depth and velocity are functions of the flow Q, both the product of the three coefficients a_i and the sum of the three exponent coefficients b_i must equal 1.

Other studies have found approximate relationships between bank-full channel dimensions of alluvial streams and rivers and their bank-full discharge. The channel dimensions, pattern and profile are primarily related to the effective or bank-full discharge. The magnitude of the bank-full discharge in the main channel typically corresponds to the 1.5- to 2-year expected return period flow event based on annual peak flows. The bank-full stage is lower than the top of the bank. It is commonly identified as a bench, a change in bank material and vegetation, or the top of a point bar (Rosgen, 1996; Ward and Elliot, 1995).

The log–log plot of Figure A.12 shows a relationship between flow rates and depths in relation to bank-full flow rates and depths for thirteen rivers in the eastern United States (Leopold et al., 1992).

The dimensionless rating curve presented in Figure A.12 shows that the annual discharge is less than the bank-full

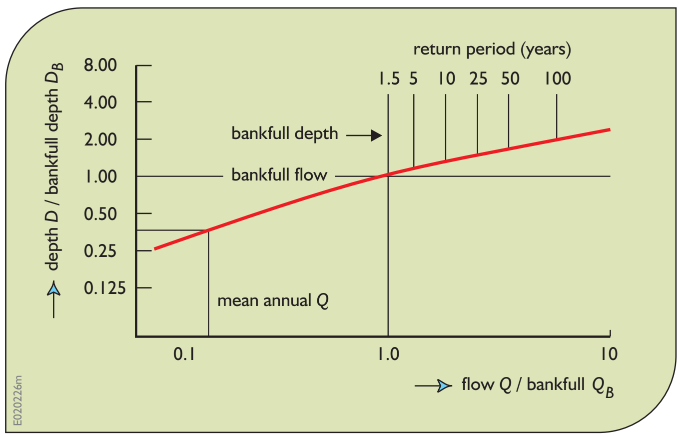

Figure A.12. Dimensionless regression curve based on thirteen gauging stations in the eastern United States (Leopold, Wolman and Miller, 1992).

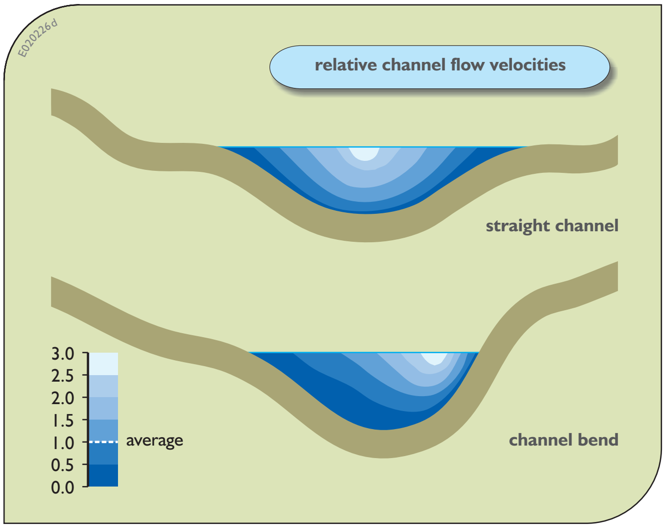

Figure A.13. Typical channel relative velocities at bank-full flows. The velocities at the outside of channel bends (the right-hand side of the lower channel) are greater than on the inside of the bends.

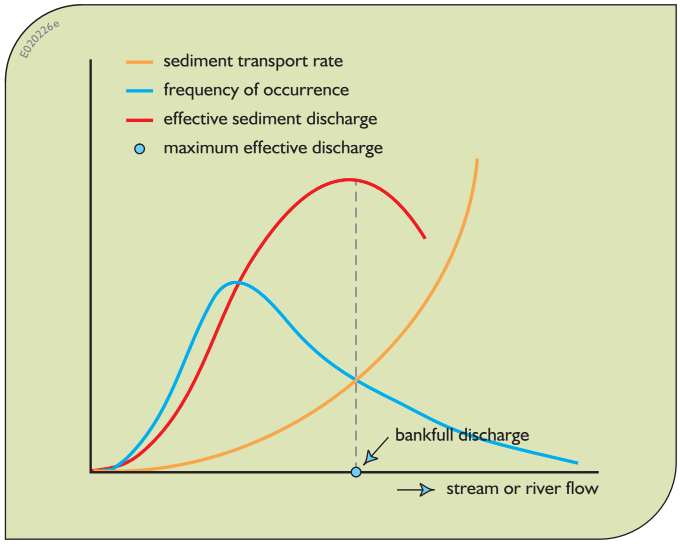

Figure A.14. The bank-full discharge typically has the largest total sediment load.

discharge and occurs at a stage of about a third of the bank-full depth. A 50- to 100-year return period discharge occurs at a stage that is about double the maximum bank-full depth. In developing a stream classification system, Rosgen (1996) defined a flood prone width as one that occurs at twice the maximum bank-full depth. Therefore, it might be expected that this depth corresponds to about the 100-year return period discharge.

2.6.4. Channel Cross Sections and Flow Velocities

Typically, flow velocity across a channel will vary from one bank to another. This lateral variation will change along a stream or river channel. For example, the velocity near the outer bank of a meander will be higher than near the inner bank because water near the outer bank has to travel further. Also, the velocity decreases towards the bottom or sides of the channel due to the surface roughness of the channel. Water in contact with the bottom and sides will be stationary. These relationships are shown in Figure A.13.

The velocity distribution in a channel can change from one cross section to the next. Typically, at any cross section in a channel, there will be a portion of the flow above the deepest point (the thalweg) that is moving the fastest. Along the thalweg the velocity increases in riffles, decreases in pools, moves from side to side, up and down with depth, and rotates as it moves around bends. The rotation of the flow on the outer bend might also create undercut concave banks.

The velocity decreases near the bottom or sides of the channel due to the roughness of its surface. Water in contact with the bottom and sides will be stationary. The changing velocities from riffles to pools will cause turbulence. Also, as water moves through pools, it will push towards the banks and away from its direction of flow. As much as a third of the flow might circulate back upstream.

The bank-full discharge is most effective in forming a channel, benches (active floodplains), banks and bars. It is this discharge rate that, as shown in Figure A.14, transports the largest total sediment load over time. The sediment concentration in the water is a function of the flow discharge rate and of course the available sediment. Low discharge rates are ineffective in transporting sediment, while high ones have very high sediment transport rates. However, extremely high discharge events occur less frequently, so the total sediment load they carry over a period of many years is not the largest.

A measure of the total sediment load carried by a particular discharge equals the event frequency multiplied by the transport rate for that discharge. The maximum value of that product for all discharges is called the *effective discharge*. This effective discharge is the bank-full discharge. It has the longest-term impact on an alluvial stream's or river's equilibrium morphology.

Discharges larger than the mean annual discharge typically transport more than 95% of the sediment in a river system.

2.6.5. Channel Bed Forms

Bed forms result from the interaction of the fluid forces and sediment particles. Bed forms in alluvial streams and rivers also depend on channel shape, size of bed material, bed vegetation and the viscosity of the fluid. In flumes having a limited range in depth and discharge, changing the slope is the principal means of changing the bed forms. In streams and rivers, however, where the slope is relatively constant, a change in bed form can occur with a change in discharge and/or a change in viscosity. Viscosity is affected by a change in sediment size distribution and/or temperature. An increase in viscosity resulting from a decrease in temperature or an increase in fine sediments such as clays can change a dune bed to washed-out dunes, plane beds or antidunes. For example, the Missouri River in the United States along the border between Iowa and Nebraska has temperatures between 21 and 27 °C in the summer and between 15 and 17 °C in the autumn. In summer, its bed form is characterized by dunes. In autumn, its bed form becomes washed-out dunes (USACE, 1969).

2.6.6. Channel Planforms

Channel planforms are what one sees when looking at them from above. Their geographic shapes can be broadly grouped into straight, meandering and braided planforms (Lagasse et al., 1991; Leopold and Wolman, 1957; Schumm, 1972, 1977; Richardson et al., 1990). These three types of channels are shown in Figure A.15. More detailed classifications have been used (Brice and Blodgett, 1978; Culbertson et al., 1967), but these three basic types are the ones most commonly considered.

A meandering stream is characterized by sinuous S-shaped flow patterns. The sinuosity of a channel of fixed

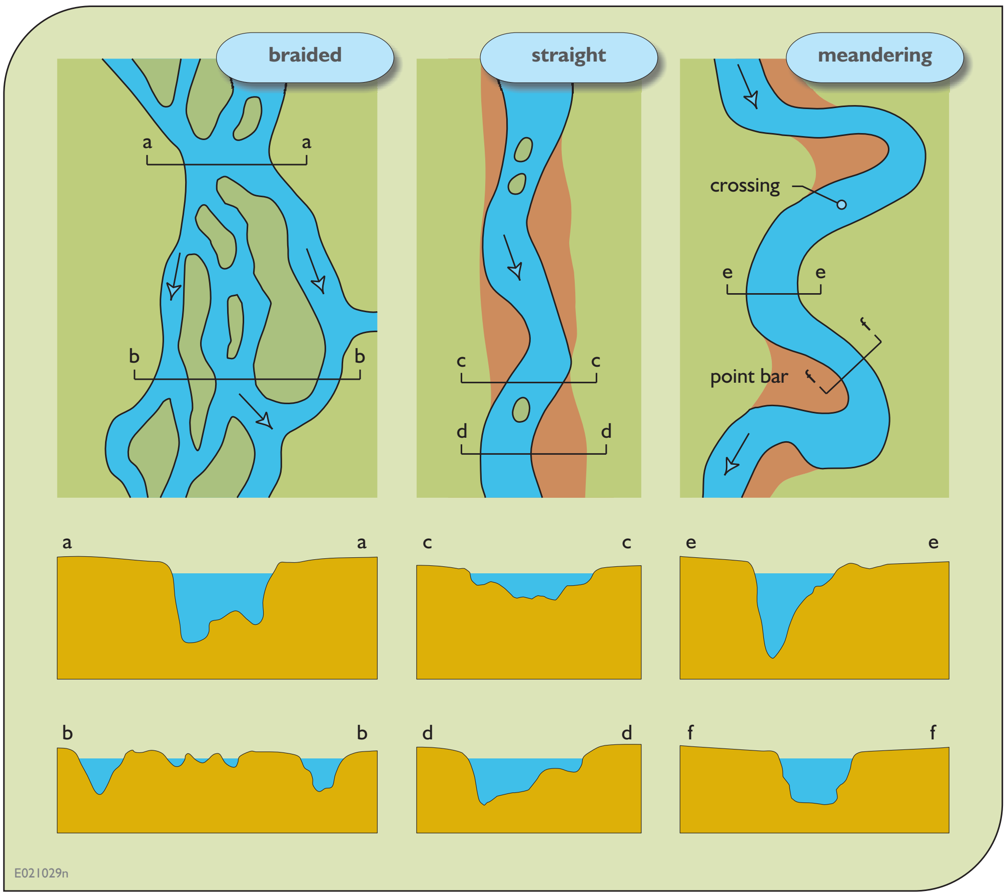

Figure A.15. Types of channel planforms (after Richardson et al., 1990).

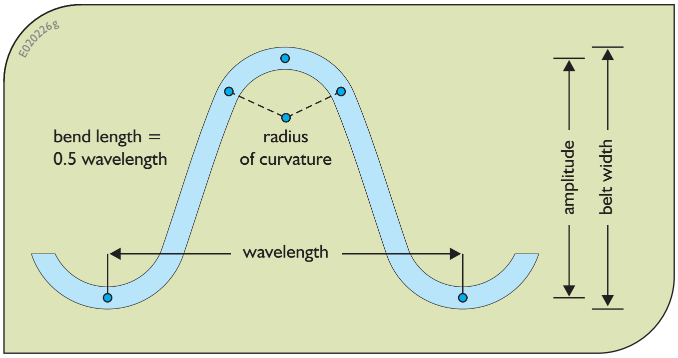

Figure A.16. Geometry of a meandering stream (Rosgen, 1996).

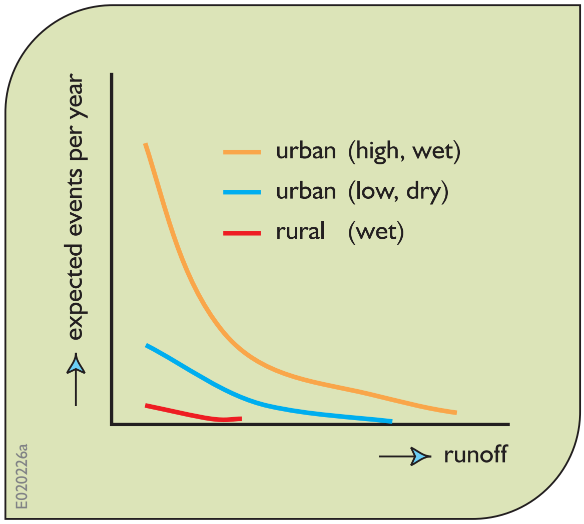

Figure A.17. Expected annual occurrences of runoff events showing the effect of high and low urban and rural development densities under wet and dry soil moisture conditions at the beginning of a storm (Ward, personal communication).

length is the ratio between its length and the straight-line distance between channel end points, or valley length. Channels can be classified according to their sinuosity. If the sinuosity is 1.0 the channel is called straight, a condition that rarely occurs in natural alluvial channels except over short distances. If the sinuosity is greater than 1.0 the channel is called sinuous. If the sinuosity is greater than about 1.4 the river is said to meander, and if the sinuosity exceeds 2.1 the degree of meandering is tortuous.

Figure A.16 defines some geometric parameters of meandering channels.

A braided stream or channel consists of a number of subordinate channels. At normal and low flow rates, these subordinate channels are separated by bars, sandbars or islands. The shape and location of the bars and islands can change with time, sometimes with each runoff event. In an anabraided stream or river, the subordinate channels are more permanent and more widely and distinctly separated than those of a braided stream.

A stream or river channel can have different planforms at different locations along its length. Channel planforms can affect channel dimensions, flows, bed material, floodplain size and plant cover. Channel planforms in turn are affected by geology, topography, the drainage area of the contributing watershed, flow velocity, discharge, sediment transport, sediment particle distribution, channel geometry, vegetation cover and any geomorphologic controls on the system.

2.6.7. Anthropogenic Factors

Stream and river morphology is affected by human activities such as changing land use, bank protection, navigation, and construction and operation of hydraulic infrastructure. Deforestation and cultivation of watershed areas, water management initiatives and floodplain development affect the runoff and the sediment yield to the river; they also influence the hydraulic roughness and the trapping of sediment during floods.

Urbanization increases the fraction of impervious land in a drainage area. This in turn reduces infiltration and causes more runoff and higher peak discharges. Sediment loads typically increase during construction and decrease following construction. All of these factors affect the equilibrium in the river and can cause it to widen and/or deepen. Channel modifications such as straightening a reach of the channel will also increase the sediment-carrying capacity of the discharge and might cause bank and bed scour.

Urbanization increases the frequency as well as the amounts of water associated with different runoff events (Figure A.17). Increasing imperviousness increases the number of expected runoff events each year. The soil moisture that exists at the beginning of a storm also influences the frequency of runoff events. In areas of Ohio in the United States, Ward (personal communication) found at the start of a storm event in a rural area with wet soil conditions there might be only one 1-cm runoff event annually and a 2-cm runoff event every few years. However, a low-density urban area or an urban area with dry soil conditions at the start of a storm event might on average experience six or seven 1-cm runoff events, two or three 2-cm events, one 2.5-cm event per year, and even an event with 3.5-cm every few years. High-density urban areas, or urban areas with wet soil conditions at the start of a storm event will on average experience more than twenty 1-cm runoff events, six 2-cm events, two 2.5-cm events, and one 3.5-cm event per year. These were for this study area in Ohio; for other areas elsewhere the numbers will differ, but the general relationships shown in Figure A.17 will apply.

The effect of urbanization on discharges is also illustrated in Figures A.18 and A.19. Rural areas will have little if any impervious cover, while urban areas will have considerably more. The plot shows the relative discharge (percentage of the rural discharge) increase that occurs as the percentage of impervious cover increases. Plots are presented for flow return periods of 2, 10 and 100 years. Note that the biggest impact is on the smaller, more frequent storm events. The two-year return period discharges, Q_2, in highly urbanized areas can be over two-and-a-half times larger than those on rural areas. In addition, as imperviousness increases, so does channel width.

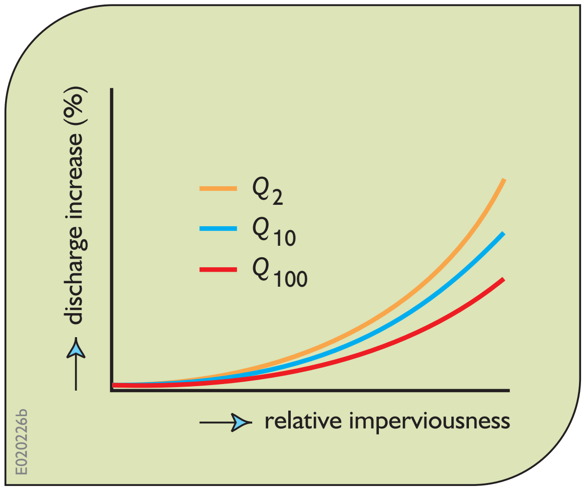

Figure A.18. Relative discharge increases, for flows having 2- 10- and 100- year return periods, as a function of degree of impervious surface area.

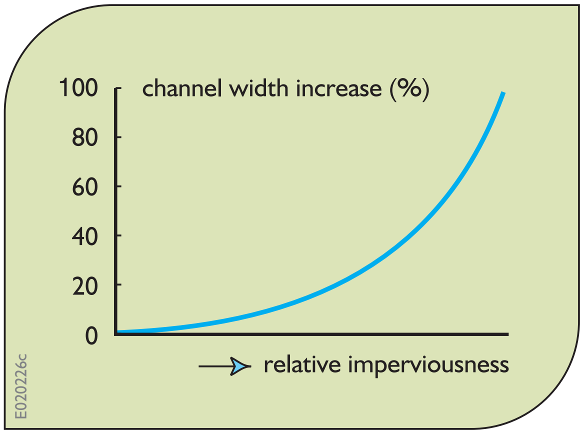

Figure A.19. Relative increase in channel width as a function of impervious surface area.

2.7. Water Quality

Establishing an appropriate flow regime in a stream or river corridor may do little to ensure a healthy ecosystem if the physical and chemical characteristics of the water are damaging to that ecosystem. For example, streams or rivers with high concentrations of toxic materials, high temperatures, low dissolved oxygen concentrations or other harmful physical/chemical characteristics cannot support healthy stream corridor ecosystems.

Figure A.20 illustrates some of the key water quality processes affecting the oxygen content and hence the biology of surface waters. (The modelling of these and other chemical and biological processes is discussed in Chapter 12.)

Dissolved oxygen (DO) is a basic requirement for a healthy aquatic ecosystem. Most fish and aquatic insects 'breathe' the oxygen dissolved in the water body. Some fish and aquatic organisms, such as carp and sludge worms, are adapted to low oxygen conditions, but most sport-fish species, such as trout and salmon, suffer when DO concentrations fall below a concentration of 3–4 mg/l. Larvae and juvenile fish are more sensitive and require even higher concentrations of DO.

Many fish and other aquatic organisms can recover from short periods of low oxygen concentrations in the water. However, prolonged episodes of depressed dissolved oxygen concentrations of 2 mg/l or less can result in 'dead' (anaerobic) water bodies. Prolonged exposure to low DO conditions can suffocate adult fish or reduce their reproductive survival rate by suffocating sensitive eggs and larvae, or starve fish by killing aquatic insect larvae and other sources of food. Low DO concentrations also favour anaerobic bacteria that produce the noxious gases often associated with polluted water bodies.

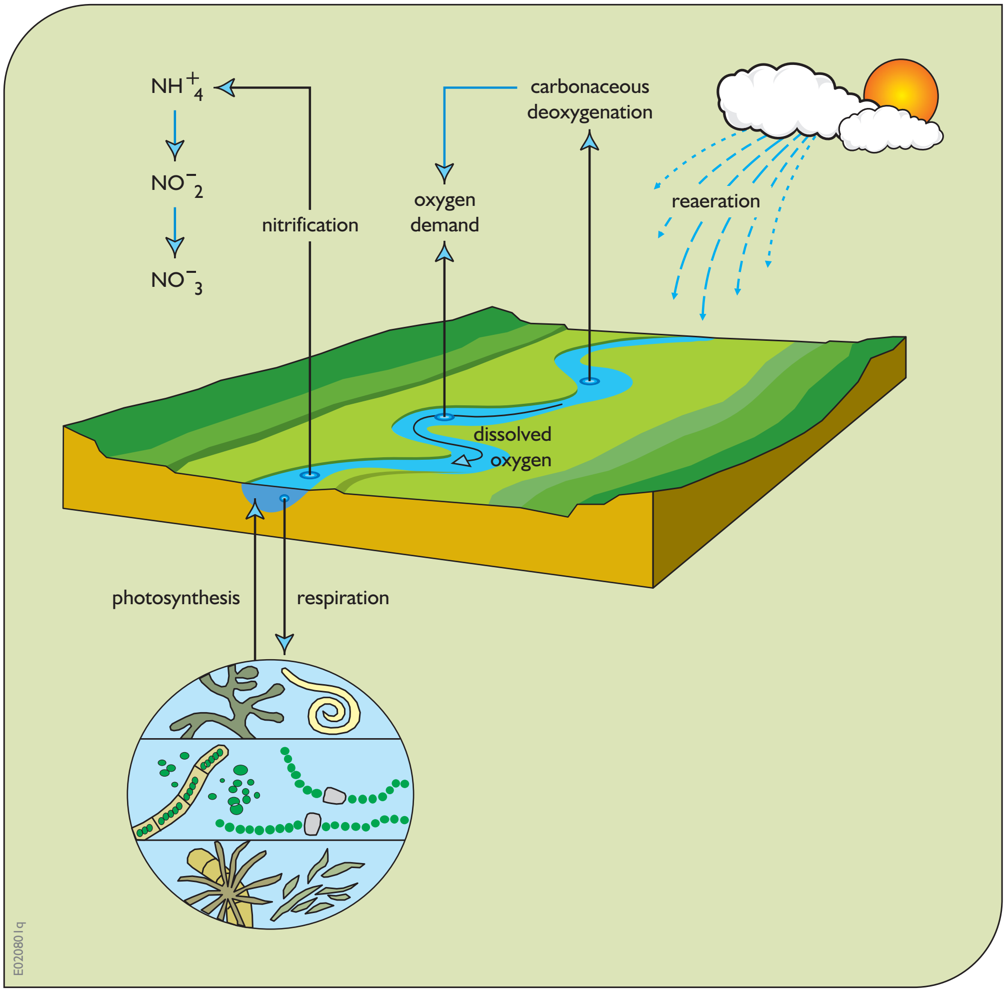

Figure A.20. Some of the basic chemical and biological processes affecting dissolved oxygen in waters.

Water absorbs oxygen directly from the atmosphere, and from plants as a result of photosynthesis. The amount of oxygen that can be dissolved in water is influenced by its temperature and salinity. Water loses oxygen primarily by respiration of aquatic plants and animals, and by the mineralization of organic matter by microorganisms. Discharges of oxygen-demanding wastes or excessive plant growth (eutrophication) induced by nutrient loading followed by death and decomposition of vegetative material can also deplete oxygen.

In addition to oxygen and water, aquatic plants require a variety of other elements to support their bodily structures and metabolism. Just as with terrestrial plants, nitrogen and phosphorus are important among these elements. Additional nutrients, such as potassium, iron, selenium and silica, are also needed by many species but are generally not limiting factors to plant growth. When any of these elements are limited, plant growth may be limited. This is an important consideration in ecosystem management.

Nutrients cycle from one form to another depending on nutrient inputs, as well as temperature and available oxygen. The nitrogen cycle is illustrated in Figure A.21 as an example. Table A.1 lists some common sources of nitrogen and phosphorus nutrient inputs and their typical concentration ranges.

Management activities can interact in a variety of complex ways with water quality. This in turn can affect ecosystem species, as shown in Figure A.22.

2.8. Aquatic Vegetation and Fauna

Stream biota are often classified in seven groups: bacteria, algae, macrophytes (higher plants), protists (amoebas, flagellates, ciliates), microinvertebrates (such as rotifers,

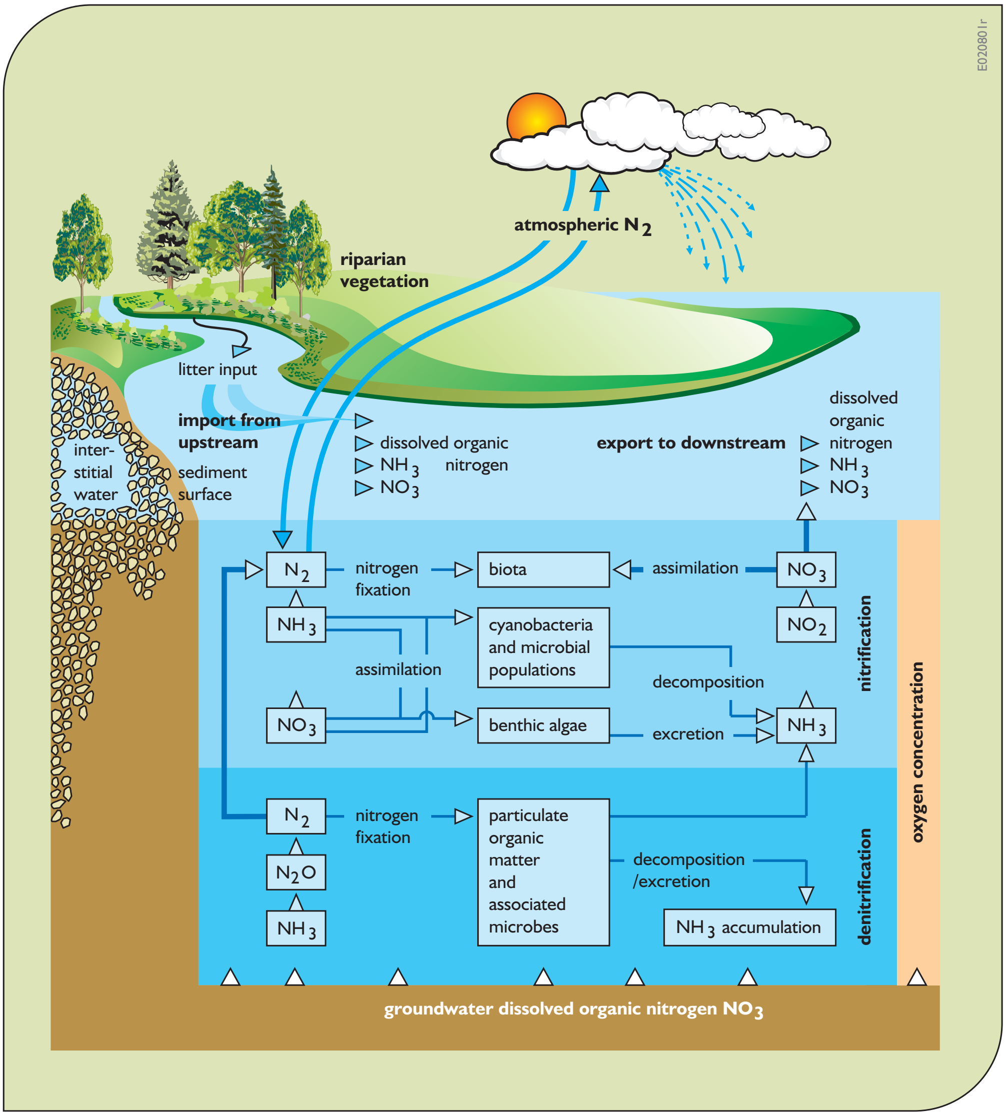

Figure A.21. Dynamics and transformations of nitrogen in a stream ecosystem.

Table A.1. Sources and concentrations of pollutants from common point and non-point sources (USDA, 1998). These data show little or no impact on nutrient removals from basic wastewater treatment facilities.

source	total nitrogen (mg/l)	total phosphorus (mg/l)
urban runoff	3-10	0.2-1.7
livestock operations	6-800	4-5
atmosphere (wet deposition)	0.9	0.015
90 % forest	0.06-0.19	0.006-0.012
50 % forest	0.18-0.34	0.013-0.015
90 % agriculture	0.77-5.04	0.085-0.104
untreated waste water	35	10
treated waste water	30	10

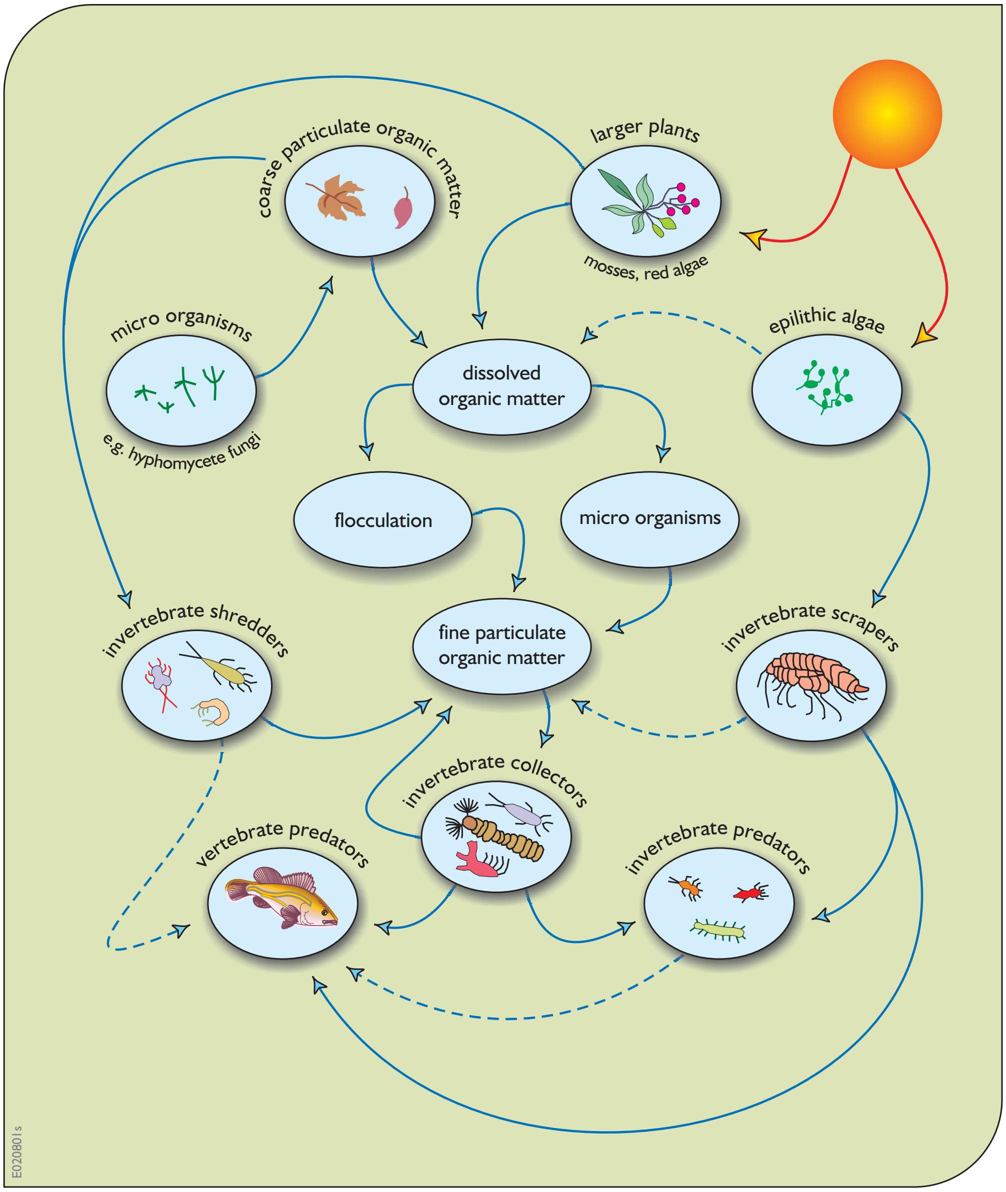

Figure A.22. Interactions among aquatic organisms and their sources of energy. (Dashed lines reflect weaker interactions.)

copepods, ostracods, and nematodes), macroinvertebrates (such as mayflies, stoneflies, caddisflies, crayfish, worms, clams, and snails) and vertebrates (fish, amphibians, reptiles, and mammals). The river continuum concept provides a framework for describing how these organisms change from lower to higher-order streams.

Much of the spatial and temporal variability of type, growth, survival and reproduction of aquatic organisms reflects variations in water quality, temperature, streamflow and flow velocity, substrate content, the availability of food and nutrients, and predator–prey relationships. These factors are often interdependent.

2.9. Ecological Connectivity and Width

Healthy ecosystems also depend on conductivity and width. Connectivity is a measure of how spatially continuous a corridor or a matrix is (Forman and Godron, 1986). A stream corridor with connections among its natural communities promotes transport of materials and energy and movement of flora and fauna. Connectivity is illustrated in Figure A.23.

Width is the distance across the stream and its zone of adjacent vegetation cover. Factors affecting width are edges, community composition, environmental gradients

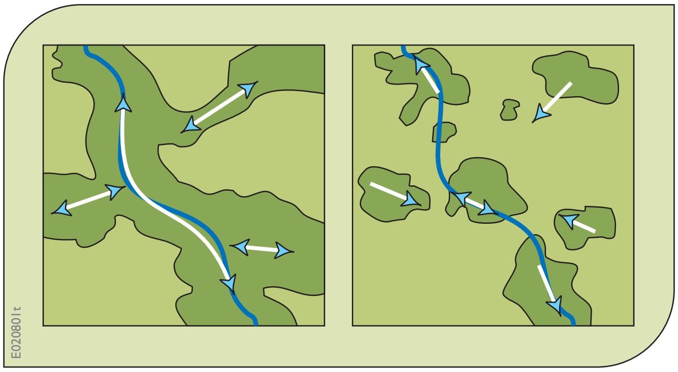

Figure A.23. Landscapes with high (left picture) and low (right picture) degrees of connectivity.

and disturbance effects of adjacent ecosystems, including those due to human activity. Width and connectivity interact throughout the length of a stream corridor. Corridor width varies along a stream and may have gaps. Gaps across the corridor can interrupt and reduce connectivity. Ensuring connectivity and adequate width can provide some of the most useful ways to mitigate disturbances.

2.10. Dynamic Equilibrium

In constantly changing ecosystems like stream and river corridors, the stability of a system is its ability to persist within a range of conditions. Within this range the system is resilient. This phenomenon is referred to as *dynamic equilibrium*.

The maintenance of dynamic equilibrium requires a series of self-correcting mechanisms in the stream corridor ecosystem. These mechanisms control the responses to external stresses or disturbances within certain ranges. The threshold levels associated with these ranges are often difficult to identify and quantify. If they are exceeded, the system can become unstable. Corridors may then undergo a change toward a new steady-state condition, usually after some time for readjustment has occurred.

Many stream systems can accommodate some disturbances and still return to functional conditions once the sources of the disturbances are removed. Ecosystems tend to heal themselves when external stresses are removed. The time it takes to do this, of course, depends on the level of stress.

2.11. Restoring Degraded Aquatic Systems

Some principles found useful in the management of restoration activities in degraded stream or river systems are listed below. These principles apply from early planning to post-implementation monitoring. They focus on scientific and technical measures and their likely impacts. Restoration activities can include upland best-management practices for agriculture, stream channel restoration, removal of exotic species and increasing native plant cover, establishing windbreaks and shelterbelts, improving upland corridors and riparian habitat, and wetland enhancement for water quality improvements. As in all management activities, the presence or absence of public support for a restoration project can make the difference between success and failure.

Preserve and Protect Aquatic Resources

Existing ecosystems that are relatively intact provide the natural materials needed for the recovery of impaired systems. It is not usually necessary to import species.

Restore Ecological Integrity

Restoration should re-establish the ecological integrity of degraded aquatic ecosystems. Ecological integrity refers to the natural structure, composition and processes of biotic communities and the physical environment. Key processes, such as nutrient cycles, succession, water levels and flow patterns, and the dynamics of sediment erosion and deposition, function within the natural range of variability. Restoration strives toward ecological integrity by taking actions that favour the desired natural processes and communities that can be sustained through time.

Restore Natural Structure and Function

Many aquatic resources in need of restoration have problems caused by past changes in channel form or other physical characteristics that led to problems such as habitat degradation, changes in flow regimes and siltation. Stream channelization, ditching in wetlands, disconnection from adjacent ecosystems and shoreline modifications are examples of such adverse changes.

Structure and function are closely linked in river corridors, lakes, wetlands, estuaries and other aquatic resources. Re-establishing the appropriate natural structure can bring back beneficial functions. For example, restoring the bottom elevation in a wetland can help re-establish the hydrological regime, natural disturbance cycles and nutrient fluxes. Monitoring the extent to which desired functions have been re-established can be a good way to determine the effectiveness of a restoration project.

Work Within the Watershed and Broader Landscape Context

Restoration requires a design based on the entire watershed or river basin, not just the part of it that is degraded. A localized restoration project may not be able to change what goes on in the whole watershed, but it can be designed to accommodate watershed effects better. New and future urban development may, for example, increase runoff volumes, streambed down-cutting, bank erosion and pollutant loading. Restoration may help mitigate these adverse effects. For example, in choosing a site for a wetland, stream or river restoration project, planners should consider how the proposed project may be used to further related efforts in the watershed, such as increasing riparian habitat continuity, reducing flooding and/or enhancing downstream water quality. Beyond the watershed, the broader landscape context also influences restoration through factors such as interactions with terrestrial habitats in adjacent watersheds, or the deposition of airborne pollutants from other regions.

Understand the Natural Potential of the Watershed

A watershed has the capacity to become only what its physical and biological setting – its climate, geology, hydrology and biological characteristics – will support. Establishing restoration goals for a water body requires knowledge of the natural range of conditions that existed on the site prior to degradation and of what future conditions might be. This information can then be used in determining appropriate goals for the restoration project.

Address Ongoing Causes of Degradation

Restoration efforts are likely to fail if the causes of degradation persist. Therefore, it is essential to identify the causes of degradation and eliminate or mitigate them wherever possible. Degradation can be caused by one event, such as the filling of a wetland, or it can be caused by the cumulative effect of numerous events, such as gradual increases in the amount of impervious surfaces in the watershed that alter the streamflow regime. In identifying the sources of degradation, it is important to look at upstream and upslope activities as well as at direct impacts on the immediate site where damage is evident. In some situations, it may also be necessary to consider downstream modifications such as dams and channelization.

Develop Clear, Achievable and Measurable Goals

Goals direct implementation and provide the standards for measuring success. The chosen goals should be achievable given the natural potential of the area and the available resources and the extent of community support for restoration. Goals provide focus and increase project efficiency. They can also change (adapt) over time.

Focus on Feasibility

Particularly in the planning stage, it is critical to focus on whether any proposed restoration activity is feasible, taking into account scientific, financial, social and other considerations. Community support for a project is needed to ensure its long-term viability. Ecological feasibility is also critical. For example, a wetland, stream or river restoration project is not likely to succeed if the hydrological regime that existed prior to degradation cannot be re-established.

Use a Reference Site

Reference sites are areas that are comparable in structure and function to the proposed restoration site before it was degraded. They may be used to identify targets for restoration projects, and as yardsticks for measuring the progress of the project. While it is possible to use historic information on sites that have been altered or destroyed, it may be most useful to identify an existing, relatively healthy, similar site as a benchmark.

Anticipate Future Changes

Although it is impossible to plan for the future precisely, foreseeable ecological and societal changes can and should be factored into restoration design. For example, in repairing a stream channel, it is important to take into account potential changes in runoff resulting from projected increases in upstream impervious surface area due to development. In addition to potential impacts from changes in watershed land use, natural changes such as plant community succession can also influence restoration. Long-term, post-project monitoring should take into account successional processes in a stream corridor when evaluating the outcome of the restoration project.

Involve the Skills and Insights of a Multidisciplinary Team

Restoration can be a complex undertaking that integrates a wide range of disciplines, including ecology, aquatic biology, hydrology and hydraulics, geomorphology, engineering, planning, communications and social science. The planning and implementation of a restoration project should involve people with experience in the disciplines needed for that particular scheme. Complex restoration projects require effective leadership to bring the various disciplines, viewpoints and styles together as an effective team.

Design for Self-Sustainability

Perhaps the best way to ensure the long-term viability of a restored area is to minimize the need for continuous operation, maintenance and repair costs, vegetation management or frequent repair of damage done by high-water events. High-maintenance approaches make long-term success dependent upon human and financial resources that may not always be available. In addition to limiting the need for maintenance, designing for self-sustainability also involves favouring ecological integrity. An ecosystem in good condition is more likely to have the ability to adapt to changes.

Use Passive Restoration, When Appropriate

Before actively altering a restoration site, determine whether simply reducing or eliminating the sources of degradation and allowing time for recovery will be enough to allow the site to regenerate naturally. There are often reasons for restoring a water body as quickly as possible, but there are other situations when immediate results are not critical. For some rivers and streams, restoring the original hydrological regime may be enough to let time re-establish the native plant community, with its associated habitat value.

Restore Native Species and Avoid Non-Native Species

Many invasive species out-compete native species because they are expert colonizers of disturbed areas and lack natural controls. The temporary disturbance present during restoration projects invites colonization by invasive species that, once established, can undermine restoration efforts and lead to further spread of these invasive species. Special attention should be given to avoiding the unintentional introduction of non-native species at the restoration site when the site is most vulnerable to invasion. In some cases, removal of non-native species may be among the primary goals of the restoration project.

Use Natural Fixes and Bioengineering Techniques, Where Possible

Bioengineering is a method of construction combining live and dead plants or inorganic materials, to produce living, functioning systems to prevent erosion, control sediment and other pollutants, and provide habitat. Bioengineering techniques can often be successful for erosion control and bank stabilization, flood mitigation and even water treatment. Specific projects can range from the creation of wetland systems for the treatment of stormwater to the restoration of vegetation on riverbanks to enhance natural decontamination of runoff before it enters the river.

Monitor and Adapt Where Changes are Necessary

Every combination of watershed characteristics, sources of stress, and restoration techniques is unique and, therefore, restoration efforts may not proceed exactly as planned. Adapting a project to at least some change or new information should be considered normal. Monitoring before and during the work is crucial for finding out whether goals are being achieved. If they are not, adjustments should be undertaken. Post-project monitoring will help determine whether additional actions or adjustments are needed, and can provide useful information for future restoration efforts. This process of monitoring and adjustment is known as adaptive implementation or adaptive management (Appendix B). Monitoring plans should be feasible in terms of costs and technology, and should provide information relevant to meeting the project goals.

3. Lakes and Reservoirs

Lakes and reservoirs are components of many river systems. They are typically dramatic and visually pleasing features of a watershed or basin. They range from pond-sized water bodies to lakes stretching for hundreds of kilometres. Referred to by some as 'pearls on a river', lakes and reservoirs can have a significant effect on the quantity and quality of the freshwater that eventually reaches the oceans.

Seen from the shoreline, a large natural lake looks much the same as a large artificial reservoir, and both often contain the word 'lake' in their name. Furthermore, the same principles of biology, chemistry and physics apply to both. Indeed, it may be difficult to discern any obvious differences between a lake and reservoir, but differences as well as similarities exist.

Lakes are water bodies formed by nature whereas reservoirs are artificial ones constructed by humans, either by damming a flowing river or by diverting water from a river to an artificial basin (impoundment). Some reservoirs are made by increasing the capacity of natural lakes. Many characteristics of lakes and reservoirs are a function of the way in which they were formed and how humans use their waters.

Lakes and reservoirs are important sources of freshwater for agriculture, industry and municipalities. At the same time, they provide habitats for a variety of species of plants and animals. They are the sources of fish, areas for migratory birds to feed, reproduce or rest, and places we all go for enjoyment and recreation. Considerable money as well as technical and scientific expertise is often required to keep them clean and healthy.

As human populations grow, greater demands are placed on the services lakes and reservoirs provide. The water levels of many lakes and reservoirs have become consistently lower as a result of higher consumption by upstream agriculture, households and industries. Increasing numbers of people enjoy the recreational activities these bodies can support, but this alters their shores, changes the surrounding land use and cover, and increases the amount of soil or sediments as well as nutrients reaching their waters. Finally, pollution from adjacent lands and various point sources may increase eutrophication processes and produce other non-desirable effects such as increased concentrations of toxic algae, reduced dissolved oxygen and generation of foul odours.

3.1. Natural Lakes

Lakes are naturally-formed, usually bowl-shaped, depressions in the land surface that have filled with water over time. These depressions were typically produced as a result of glaciers, volcanic activity or tectonic movements. The age of most permanent lakes is usually of a geological time frame. Some ancient lakes may be millions of years old.

The most significant past mechanism for the formation of lakes in temperate areas was the natural process of 'glacial scour', in which the slow movement of massive volumes of glacial ice during and after the Ice Age produced depressions in the land surface that subsequently filled with water. The North American Great Lakes (Superior, Michigan, Huron, Erie and Ontario), lakes in the Lake District of the United Kingdom, and the numerous lakes in Scandinavia and Argentina are prominent examples of this type of lake formation. Some smaller 'kettle lakes', as found on Cape Cod in Massachusetts, for example, were formed by the deposition and subsequent melting of glacial ice blocks.

Another major lake formation process was 'tectonic movement', in which slow movements of the earth's crust gradually produced depressions that were subsequently filled with water. Lake basins also formed as a result of volcanic activity, which also produced depressions in the land surface. Most of the earth's very deep lakes resulted from either volcanic or tectonic activity. Lake Baikal in Russia, the world's deepest lake, which contains approximately 20% of the world's liquid freshwater, and the African Rift Valley lakes are prominent examples of this tectonic type of lake formation.

Other natural processes that produced lake basins include seepage of water down through layers of soluble rock, erosion of the land surface by wind action, and plant growth or animal activity (such as beaver dams) that resulted in blocking the outlet channels from shallow depressions in the land surface.

There are literally millions of small lakes around the world, concentrated largely in the temperate and sub-arctic regions. These regions are also characterized by a relative abundance of freshwater. Many more intermittent lakes occur in semi-arid and arid regions.

3.2. Constructed Reservoirs

In contrast to natural processes of lake formation, reservoirs are water bodies that are usually formed by constructing a dam across a flowing river. A dam may sometimes also be constructed on the outlet channel of a natural lake as a means of providing better control of the lake's water level (examples include Lake Victoria in Africa, and Lake Tahoe in the United States). However, these latter water bodies typically retain their natural lake characteristics.

Reservoirs are found primarily in areas with relatively few natural lakes, or where the lakes do not satisfy human water needs. Reservoirs are much younger than lakes, with life spans expressed in terms of historical rather than geological time. Although lakes are used for many of the same purposes as reservoirs, a distinct feature of the latter is that they are usually built to address specific water needs. These include municipal and drinking water supplies, agricultural irrigation, industrial and cooling water supplies, power generation, flood control, sport or commercial fisheries, recreation, aesthetics and/or navigation. Small reservoirs are sometimes built for fire protection as well.

The reasons for constructing reservoirs are ancient in origin, and have focused on the need of humans to ensure a more reliable water supply and to protect themselves during periods of floods. Accordingly, reservoirs are usually found in areas of water scarcity, or where a controlled water facility was necessary. Small reservoirs were first constructed some 4,000 years ago in China, Egypt and Mesopotamia, primarily to supply drinking water and for irrigation purposes. Simple small dams were constructed by blocking a stream with soil and brush, in much the same manner as beavers dam a stream. Larger reservoirs were constructed by damming a natural depression, or by forming a depression along the river and digging a channel to divert water to it from the river. Early irrigation practices were linked largely to land adjacent to streams. They required the construction of larger dams that allowed humans to impound larger volumes of water. Later reservoirs were also used as sources of power, first to drive waterwheels and subsequently to produce hydroelectric power.

3.3. Physical Characteristics

Like lakes, reservoirs range in size from pond-like to very large water bodies. The variations in type and shape, however, are much greater than for lakes. The term 'reservoir' includes different types of constructed water bodies and/or water storage facilities. These are (1) valley reservoirs, created by constructing a barrier (dam) perpendicular to a flowing river; and (2) off-river storage reservoirs, created by constructing an enclosure parallel to a river, and subsequently supplying it with water either by gravity or by pumping from the river. The latter reservoirs are sometimes also called embankment or bounded or pumped-storage reservoirs. They have controlled inflows and outflows to and from one or more rivers. For example, much of the water in the river above Niagara Falls between Canada and the United States is diverted to a pumped storage reservoir during the night and released through hydroelectric generators during the day when the energy demand, and hence price, is higher.

In addition to single reservoirs, reservoir systems also exist. These may be (1) cascade reservoirs, consisting of a series of reservoirs constructed along a single river; or (2) inter-basin transfer schemes, designed to move water through a series of reservoirs, tunnels and/or canals from one drainage basin to another. These types are illustrated in Figure A.24.

Much of our current limnological knowledge (including that used to manage lakes and reservoirs) has come from studies of lakes over many decades. Although we now have a reasonable understanding of physical and biological processes that take place in lakes, we are less advanced in our understanding of these processes in reservoirs. Many early reservoir studies focused on sediment loading from drainage basins. The rationale for this was that the rate at which a reservoir filled with sediment is a major determinant of useful operational life. Comparatively little attention was given to the environmental and socioeconomic issues associated with reservoir construction. That situation has changed.

3.3.1. Shape and Morphometry

The shape of lakes and reservoirs is determined largely by how they were formed. This also affects some of their fundamental characteristics. Because lakes are naturally-formed, bowl-shaped depressions typically located in the

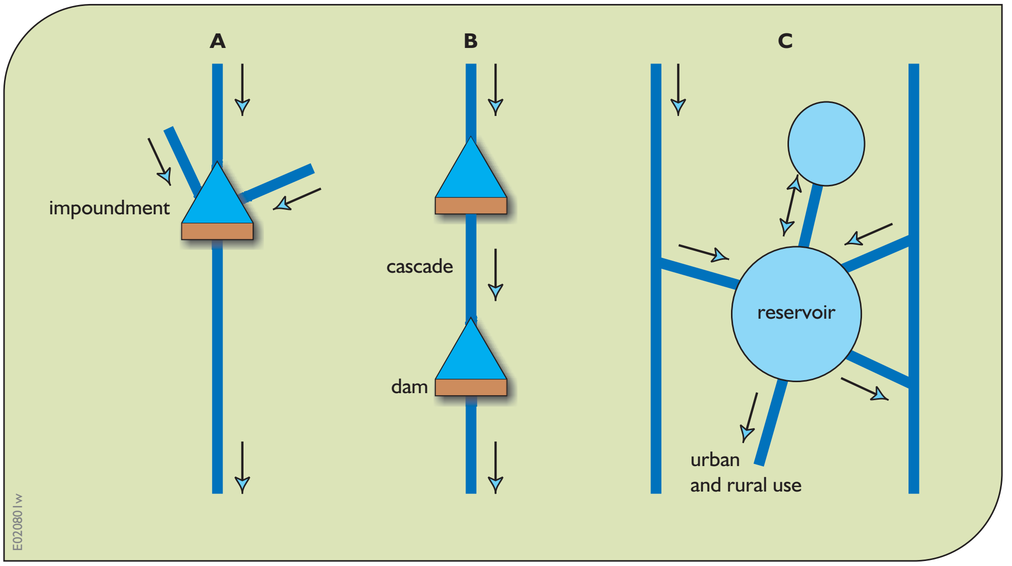

Figure A.24. Types of reservoir arrangements, ranging from (left to right) a single reservoir to a cascade of reservoirs along a river, to pumped storage reservoirs adjacent to rivers.

central part of a drainage basin, they usually have a more rounded shape than reservoirs. As in a bowl, the deepest part of a lake is usually at its centre. The shallowest part of the water basin is usually located near the outflow channel.

In contrast, a reservoir often has its deepest part near the dam. Moreover, because a river often has a number of streams or tributaries draining into it, when it is dammed the impounded water tends to back up into the tributaries. As a result, some reservoirs have a characteristic dendritic shape, with the 'arms' radiating outward from the main body of the reservoir as illustrated in Figure A.25. In contrast, a reservoir formed by damming a river with high banks will tend to be long and narrow. Depending on how they were constructed, off-river storage reservoirs can have many shapes.

The dendritic or branching form of many reservoirs provides a much longer shoreline than associated with lakes of similar volume. Reservoirs also usually have larger drainage basins. Because of their larger basins and multiple tributary inputs, the flow of water into reservoirs is more directly tied to precipitation events in the drainage basin than it is in lakes. Also, the fact that the deepest parts of most reservoirs are just upstream of the dam facilitates the possibilities for draining the reservoir.

Damming a river inundates land previously above water, and sometimes forces the relocation of inhabitants and wildlife living around the river. The presence of a dam downstream also allows a greater degree of control of water levels and volumes for reservoirs than for lakes. Constructing water discharge structures at different levels

Figure A.25. Characteristic dendritic shape of a large reservoir created by a dam to the right of this figure.

in the dam allows withdrawal or discharge of water from selected depths in a reservoir. 'Selective withdrawal' (as shown in Figure A.26) has major implications for the water-mixing characteristics and increases flushing possibilities for reservoirs.

3.3.2. Water Quality

The characteristics of river water typically undergo changes as the water enters the lake or reservoir. Primarily because of reduced velocities, sediment and other

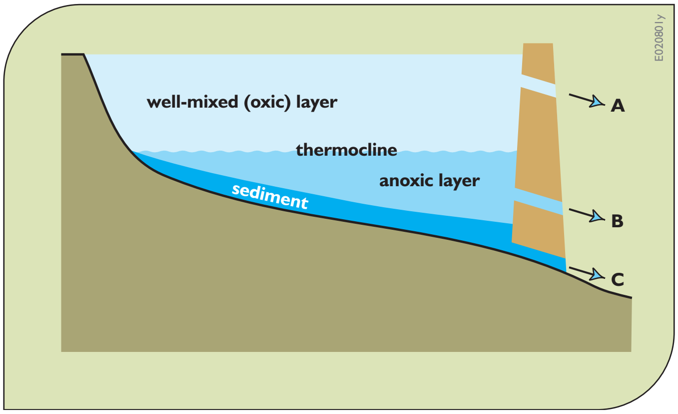

Figure A.26. Multiple outlets from a dam permit some control of water quality as well as quantity downstream.

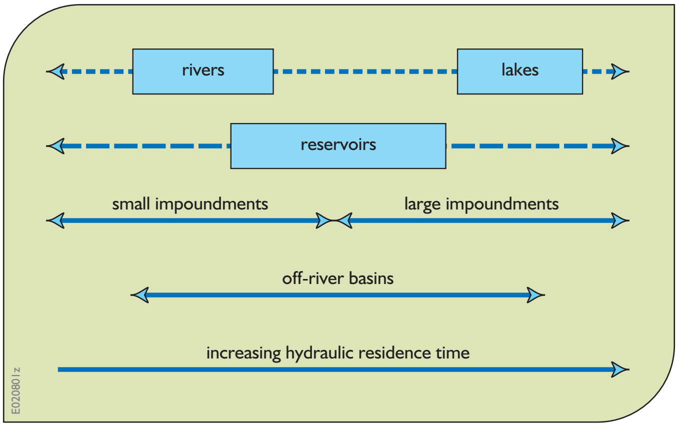

Figure A.27. A comparison of typical hydraulic residence times of rivers, reservoirs and lakes.

materials carried in the water settle out in the lake or reservoir. The structure of the biological communities also changes from organisms suited to living in flowing waters to those that thrive in standing or pooled waters. Pooled waters provide greater opportunities for the growth of algae (phytoplankton) that can lead to eutrophication.

Reservoirs typically receive larger inputs of water, as well as soil and other materials carried in rivers, than do lakes. As a result, they usually receive larger pollutant loads. However, because of greater water inflows, flushing rates are typically more rapid than in lakes (Figure A.27). Thus, although reservoirs may receive greater pollutant loads, they have the potential to flush the pollutants more rapidly. Reservoirs may therefore exhibit fewer or less severe negative water quality or biological impacts than lakes for the same pollutant load.

Although there are many variables of limnological significance, water quality is typically characterized on the basis of such variables as water clarity or transparency, concentration of nutrients and algae, oxygen concentration, concentration of dissolved minerals and acidity.

Waste chemical compounds from industry, some with toxic or deleterious effects on humans and/or water-dependent products, can be part of the pollution load discharged into lakes and reservoirs. These loads can kill aquatic organisms and damage irrigated crops. The quantity of bacteria, viruses and other organisms in waste-receiving waters are a primary cause of water-borne disease. Although such organisms present a risk to human health worldwide, such risks are particularly severe in developing countries.

There are some major differences between deep and shallow lakes and reservoirs. Deep water bodies, particularly in non-tropical regions, usually have better water quality in their lower layers. Shallow water bodies do not exhibit this depth differentiation in quality. Their more shallow, shoreline areas have relatively poorer water quality, because those areas are where pollutant inputs are discharged and where there is a greater potential for disturbance of bottom muds. Thus, the water quality of a natural lake usually improves from the shoreline to the deeper, central part. In contrast, the deepest end of a reservoir is immediately upstream of the dam, so that water quality usually improves along the length of a reservoir, from the shallow inflow end to the deeper, 'lake-like' end near the dam.

Reservoirs, particularly the deeper ones, are also distinguished from lakes by the presence of a longitudinal gradient in physical, chemical and biological water quality characteristics from the upstream river-end to the downstream dam-end. Thus, reservoirs have been characterized as having three major zones: an upstream riverine zone, a downstream lake-like zone at the dam-end, and a transitional zone separating these two zones (Figure A.28). The relative size and volume of the three zones can vary greatly in a given reservoir.

3.3.3. Downstream Characteristics

The construction of a dam can change the downstream river channel below it. Because reservoirs act as sediment and nutrient traps, the water at the dam-end of a reservoir is typically of higher quality than the water entering it.

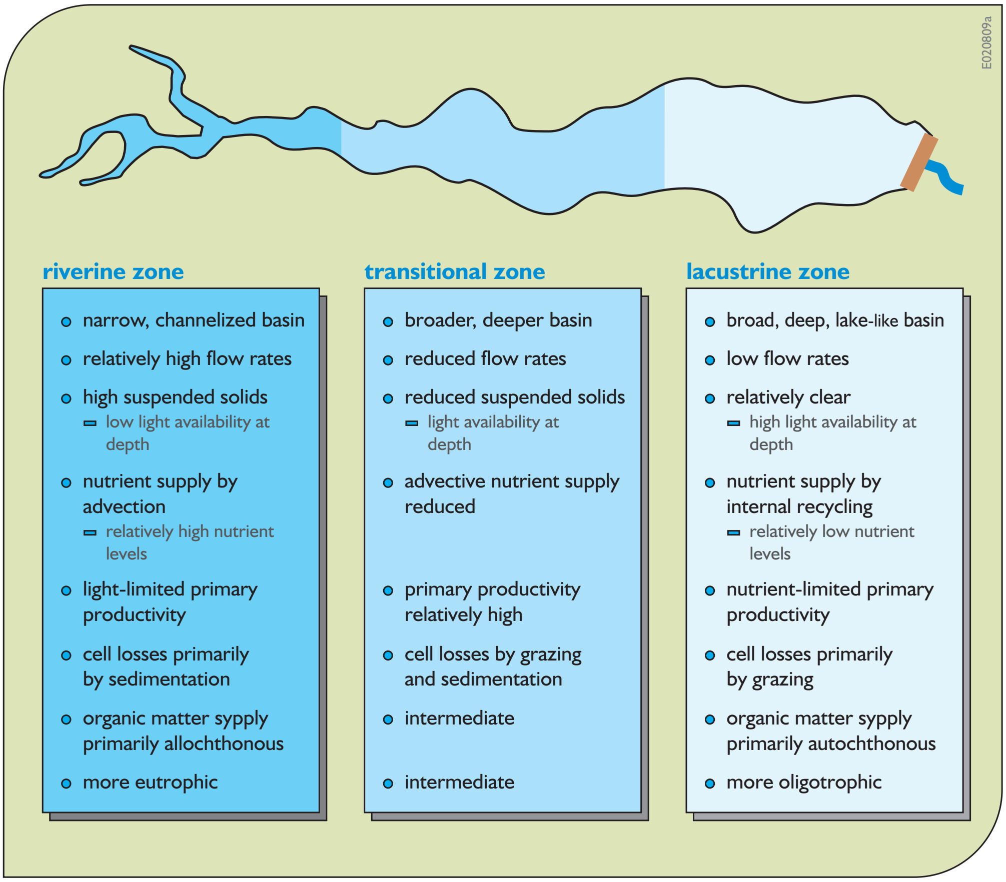

Figure A.28. Characteristics of three longitudinal zones in a reservoir.

This higher-quality water subsequently flows into the downstream river channel below the dam. The smaller the quantity of sediments and other materials transported in the discharged water, the greater the quantity of sediment that can be picked up and transported as it moves downstream. This scouring effect can have a negative impact on the flora, fauna and biological community structure in the downstream river channel. The removal and deposition of sediments from floodplains can also affect the biological character of those floodplains.

Many reservoirs, especially those used for drinking water supplies, have water release or discharge structures located at different vertical levels in their dams (Figure A.26). This allows for the 'selective withdrawal' or discharge of water from different layers within the reservoir. Depending on the quality of the water discharged, selective withdrawal can affect water quality within the reservoir itself, as well as the chemical composition and temperature of the downstream river. The ability to regulate or schedule water, temperature and silt discharges can provide some control on the hydrological regimes, affecting both flora and fauna.

Constructing a reservoir to protect downstream areas from floods often has significant social and economic implications, including the potential for stimulating urban and agricultural development adjacent to, and below, the reservoir. This can have both positive and negative impacts, depending on the nature and size of development. Appendix D discusses this aspect of flood management in more detail.

Table A.2 summarizes some of the major characteristics of lakes and reservoirs.

3.4. Management of Lakes and Reservoirs

Because drainage basins are simultaneously the sources of water, the places where the water is usually used, and the points where human activities affect both water quantity and quality, they are usually considered the logical management unit for lakes and reservoirs. However, activities that generate pollutants (such as urbanization, industrialization and agricultural production) may occur outside the affected drainage basin. They still need to be considered when developing management plans for lakes or reservoirs.

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Table A.2. Comparison of major characteristics of lakes and reservoirs.

lake	reservoir
especially abundant in glaciated areas; orogenic areas are characterized by deep, ancient lakes; riverine and coastal plains are characterized by shallow lakes and lagoons	located worldwide in most landscapes, including tropical forests, tundra and arid plains; often abundant in areas with a scarcity of natural lakes
generally circular water basin	elongated and dendritic water basin
drainage: surface area ratio usually $<10:1$	drainage: surface area ratio usually $>10:1$
stable shoreline (except for shallow, lakes in semi-arid zones)	shoreline can change because of ability to artificially regulate water level
water level fluctuation generally small (except for shallow lakes in semi-arid zones)	water level fluctuation can be great
long water flushing time in deeper lakes	water flushing time often short for their depth
rate of sediment deposition in water basin is usually slow under natural conditions	rate of sediment deposition often rapid
variable nutrient loading	usually large nutrient loading their depth
slow ecosystem succession	ecosystem succession often rapid
stable flora and fauna (often includes endemic species under undisturbed conditions)	variable flora and fauna
water outlet is at surface	water outlet is variable, but often at some depth in water column
water inflow typically from multiple, small tributaries	water inflow typically from one or more large rivers

Point sources of pollutants are ‘pipeline’ discharges to receiving waters. These are relatively easy to identify and isolate. In contrast, non-point pollution results from storm runoff or snowmelt that transports polluting materials diffusely and over urban or agricultural lands to streams, rivers, lakes and reservoirs. Non-point source pollution is closely tied to precipitation and runoff events. It is less predictable and more variable than pollutants from point sources and groundwater flows. Because of their diffuse nature, pollutants from non-point sources are more difficult to identify and control. Chapter 13 contains a more detailed discussion of this problem, especially from urban areas.

Of particular importance in addressing lake and reservoir management problems is the need to consider the affected ecosystems as well as the direct economic benefits lakes and reservoirs can provide. Managers must balance the water needs of economic development with the need to protect and preserve the environment and its ecosystem.

Many environmental and ecosystem processes in reservoirs and downstream rivers are complex, long term and ‘non-traditional’ from the perspective of current understanding of lake and river limnology. Some non-traditional processes exist because reservoirs are often intermediate aquatic systems representing transitions between flowing rivers and lakes (Figure A.28). Our limnological understanding of these processes is relatively young.

The presence of a reservoir in a drainage basin where no such water body previously existed can obviously affect the watercourse, its flora and fauna, and the human inhabitants in the drainage basin. These potential impacts should be identified and analysed prior to reservoir construction. The results of procedures to identify and properly evaluate potential environmental, social and economic consequences of reservoir construction are included in environmental impact assessment reports. In many countries such assessments are now required by law for all new dam construction.

3.5. Future Reservoir Development

Nearly all major river systems in the world have reservoirs in their drainage basins. A number of river systems (such as the Angara, Columbia, Dnieper, Missouri, Mosel, Parana and Volga) also have cascades of reservoirs within their basins. Reservoirs exist on all continents (except Antarctica) and in all countries, although their distribution within specific countries and regions is irregular. Construction of new reservoirs has all but ceased in North America and Europe. In contrast, reservoir construction is continuing in developing countries, with nearly all new reservoirs scheduled to enter operation in the twenty-first Century located in the Middle East, Asia, Africa and Latin America.

Reservoirs represent important components of the social and economic infrastructure of both developed and developing countries. In some cases, these have generated public and international concern, as in the cases of the Sardar Sarovar Dam in India and the Three Gorges Dam in China. Proponents of large dams argue that they bolster local economies, improve electrical energy supplies, provide needed flood control, and help humans manage the world's water resources more effectively. Opponents of large dams say that they cause significant damage to the environment and the local culture, and produce little overall economic gain. These conflicting points of view require attention early in the planning stage to ensure that they are properly considered by all relevant parties and interests prior to initiation of construction activities.

The Sanmenxia Dam on the Yellow River, China, provides an example of problems that were not sufficiently considered prior to dam construction. Finished in 1960, the project's goals were to prevent floods, provide water for irrigation and produce hydroelectric power. However, significant silt loads in the Yellow River were not adequately considered in the planning stage. The reservoir water basin was largely filled with silt only four years after construction, and the reservoir was subsequently taken out of operation.

Another example is the construction of the Aswan High Dam that impounds the Nile River in southern Egypt. The dam has now been in operation for about half a century, and both positive and negative impacts have resulted from its construction. The positive economic impacts include an improvement of summer crop rotations and guaranteed availability of irrigation water for agricultural production, expanded rice cultivation, conversion of about a million acres from seasonal to perennial irrigation, an expansion of about 486 thousand hectares of new agricultural and industrial land due to increased water availability, protection from high floods and droughts, generation of significant quantities of hydroelectric power, improved navigation possibilities and increased tourism.

The negative environmental and social impacts include declining water levels at Nile River barrages downstream of the dam, rising water levels upstream of the Delta Barrage, increased riverbank erosion and river meandering, production of river channel scour holes downstream of existing river barrages, decreased water quality due to increased industrial and agricultural discharges, increased reservoir siltation, increased reservoir eutrophication, increased water evaporation, increased coastal erosion at the mouth of the Nile River, decreased human health due to increased incidence of schistosomiasis and spread of water-related vectors, and inundation of historical monuments.

The overall conclusion of most observers is that the Aswan High Dam has had an overall positive effect, although it contributed to some significant environmental problems as well. Continued studies will undoubtedly provide additional information and guidance to those considering the construction of large dam projects in future years, particularly in developing countries.

Table A.3 summarizes some of the possible effects, both beneficial and damaging, of large reservoirs.

4. Wetlands

Wetlands are areas of frequent and prolonged presence of water at or near the soil surface. Swamps, marshes and bogs are well-recognized types of wetlands. Others less known include vernal pools (pools that form in the spring rains but are dry at other times of the year), playas (areas at the bottom of undrained desert basins that are sometimes covered with water) and prairie potholes. Some well-known wetlands, such as the Everglades in South Florida and the Mississippi bottomland hardwood swamps in the United States, can be completely dry at times. In contrast, many upland areas that are not considered wetlands can be very wet during and shortly after wet weather.

Table A.3. Possible positive and negative effects of large reservoir construction.

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positive benefits	negative effects
• production of energy (hydropower) • increased low-energy water quality improvement • retention of water resources in the drainage basin • creation of drinking water and water supply resources • creation of representative biological diversity reserves • increased welfare for local population • enhanced recreational possibilities • increased protection of downstream river from flooding events • increased fishery possibilities • storage of water for use during low-flow periods • enhancement of navigation possibilities • increased potential for sustained agricultural irrigation	• displacement of local populations following inundation of reservoir water basin • excessive human immigration into reservoir region, with associated social, economic and health problems • deterioration of conditions for original population • increased health problems from increasing spread of waterborne disease and vectors • loss of edible native river fish species • loss of agricultural and timber lands • loss of wetlands and land/water ecotones • loss of natural floodplains and wildlife habitats • loss of biodiversity, and displaced wildlife populations • need for compensation for loss of agricultural lands, fishery grounds and housing • degradation of local water quality • decreased river flow rates below reservoir, and increased flow variability • decreased downstream temperatures, transport of silt and nutrients • decreased concentrations of dissolved oxygen and increased concentrations of hydrogen sulfide and carbon dioxide in reservoir bottom water layer and dam discharges • barrier to upstream fish migration • loss of valuable historic or cultural resources (e.g., burial grounds, relic sites, temples) • decreased aesthetic values • increased seismic activity

4.1. Characteristics of Wetlands

When the upper part of the soil is saturated with water at growing season temperatures, organisms consume the oxygen in the soil and cause conditions unsuitable for most plants. Such conditions also cause the development of so-called 'hydric soils'. Plants that can grow in these conditions, such as marsh grasses, are called 'hydrophytes'. The presence of hydric soils and hydrophytes can indicate the existence of wetlands.

Wetlands are classified as either marine, estuarine, lacustrine, riverine or palustrine. Marine and estuarine wetlands are associated with the ocean and include coastal wetlands, such as tidal marshes. Lacustrine wetlands are associated with lakes, while riverine wetlands are found along rivers and streams. Palustrine wetlands may be isolated or connected wet areas and include marshes, swamps and bogs (Cowardin et al., 1979). A palustrine system can exist directly adjacent to or within lacustrine, riverine or estuarine systems.

Wetlands store precipitation and surface water and then slowly release the water into associated surface water resources, groundwater and the atmosphere. Wetland types differ in this capacity based on a number of physical and biological characteristics, including landscape position, soil saturation, the fibre content/degree of

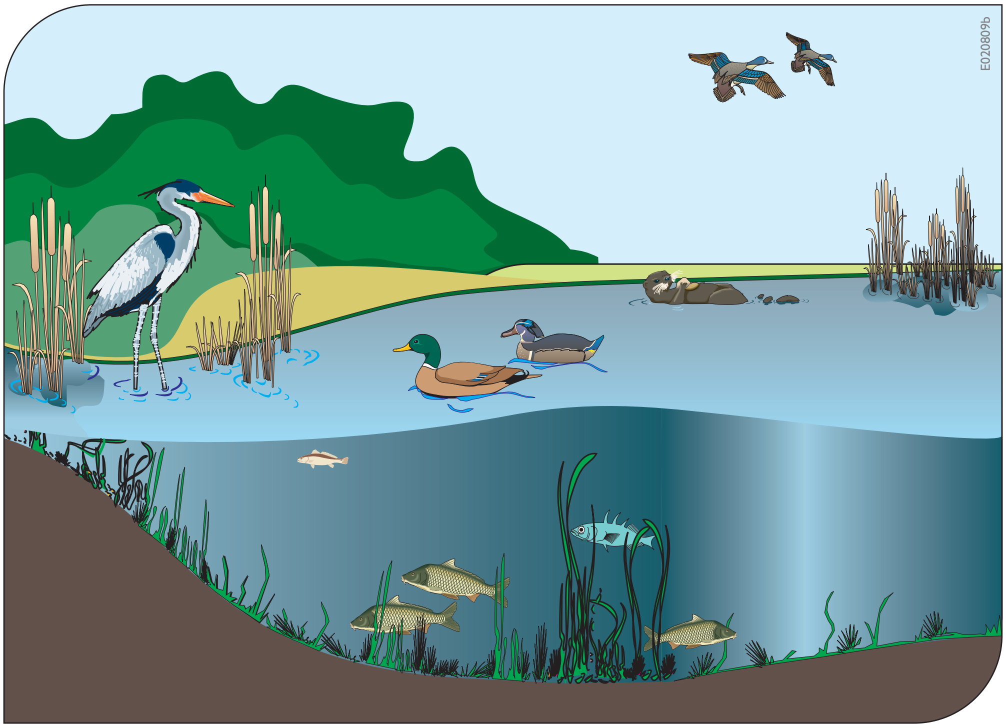

Figure A.29. Wetlands support a productive food web, from microscopic algae and submerged vascular plants to, in some areas, great blue herons and otters.

decomposition of the organic soils, vegetation density and type of vegetation.

4.1.1. Landscape Position

Landscape position affects the amount and source of water in a wetland. For example, wetlands that are near the top of a watershed, such as a mountain bog, will not receive as much runoff as marshes in low areas. Wetlands can result from precipitation, groundwater or surface flow. Precipitation-dominated wetlands can be in flat or slightly elevated areas in the landscape, where they receive little or no surface runoff. Generally such wetlands have a clay and peat layer that retains the precipitation and also prevents discharge from groundwater. Wetlands also form in areas of active groundwater discharge, particularly at the base of hills and in valleys. These groundwater-dominated wetlands may also receive overland flow but they have a steady supply of water from and to groundwater. Many wetlands in low points on the landscape are dominated by overland flow. Such riverine, fringe (marsh) and tidal wetlands actively influence the landscape since they come in contact with, store or release large quantities of water and act upon sediments and nutrients. Surface water provides the major source of water for these wetlands.

4.1.2. Soil Saturation and Fibre Content

Soil saturation and fibre content affect the capacity of a wetland to retain water. As in a sponge, as the pore spaces in wetland soil and peat become saturated by water, they are able to hold less additional water and release the water more easily. Clay soils retain more water than loam or sand. They hold the water particles more tightly through capillary action, since pore spaces are small and the water particles are attracted to the negatively-charged clay. Pore spaces between sand particles are larger and water drains more freely, since less of the water in the pores is close enough to be attracted to the soil particle.

Water in wetlands flows over or close to the surface in the fibric layer and root zone. Wetlands with sapric peat (mostly decomposed, unrecognizable fibres) and clay substrate will store water but will have no groundwater inflow or outflow.

4.1.3. Vegetation Density and Type

Plants growing in wetlands transpire water. Their stems reduce the velocity of water flowing through the wetland. As vegetation density increases, flow velocity decreases. Sturdy plants, such as shrubs and trees, cause more friction than do grasses.

Plant transpiration reduces the amount of water in wetland soil and increases the capacity to absorb additional water. As a result, water levels and outflows from the wetland are less during the growing season than when plants are dormant. Obviously larger plants and plants with greater surface area will take up and transpire more water than will smaller or less dense plant communities.

4.1.4. Interaction with Groundwater

Some wetlands in low-lying areas are fed by groundwater discharges. Most other wetlands are a source of groundwater recharge. The extent of groundwater recharge by a wetland is dependent upon soil, vegetation, site, perimeter–volume ratio and water table gradient. Groundwater recharge occurs through mineral soils found primarily around the edges of wetlands; the soil under most wetlands is relatively impermeable. A high perimeter–volume ratio, as found in small wetlands, means that the surface area through which water can infiltrate into the groundwater is relatively high. Groundwater recharge is typical in small wetlands such as prairie potholes.

4.1.5. Oxidation–Reduction

The fluctuating water levels (also known as hydrological flux) that are characteristic of wetlands control the oxidation–reduction (redox) processes that occur. These redox processes, governed by the frequency, duration and timing of wetland flooding (hydroperiod), play a key role in nutrient cycling, availability and export; pH; vegetation composition; sediment and organic matter accumulation; decomposition and export; and metal availability and export.

When wetland soil is dry, microbial and chemical processes occur, using oxygen as the electron acceptor. When wetland soil is saturated with water, microbial respiration and biological and chemical reactions consume available oxygen. The soil changes from an aerobic to an anaerobic, or reduced, condition. As conditions become increasingly reduced, other electron acceptors than oxygen must be used for reactions. These acceptors are, in order of microbial preference, nitrate, ferric iron, manganese, sulphate and organic compounds.

Wetland plants are adapted to changing redox conditions, and often contain spongy tissue with large pores in their stems and roots. This allows air to move quickly between the leaf surface and the roots, from which oxygen is released to oxidize the root zone (rhizosphere) and allow processes requiring oxygen, such as organic compound breakdown, decomposition and denitrification, to occur.

4.1.6. Hydrological Flux and Life Support

Changes in the frequency, duration and timing of hydroperiods may affect spawning, migration, species composition and food chain support of the wetland and associated downstream systems. Normal hydrological flux allows exchange of nutrients and detritus and passage of aquatic life between systems.

Values of, or services provided by, wetlands as a result of the functions of hydrological flux and storage include enhanced water quality, water supply reliability, flood control, erosion control, wildlife support, recreation, and cultural and commercial benefits.

4.2. Biogeochemical Cycling and Storage

Wetlands may serve as sinks for nutrients, organic compounds, metals and components of organic matter. They may also act as filters of sediments and organic matter. A wetland may be a permanent sink for these substances if the compounds become buried in the substrate or are released into the atmosphere. Alternatively, it may retain them only during the growing season or under flooded conditions. Wetland processes play a role in the cycles of carbon, nitrogen and sulphur by transforming them and releasing them into the atmosphere (see, for example, the nitrogen cycle in Figure A.21).

Decomposition rates vary across wetland types, particularly as a function of climate, vegetation types, available carbon and nitrogen, and pH. A pH above 5.0 is necessary for bacterial growth and survival. Liming, to increase pH, accelerates decomposition, causing the release of carbon dioxide from wetlands and land subsidence.

The nutrients and compounds released from decomposing organic matter may be exported from the wetland in soluble or particulate form, incorporated into the soil, or eventually transformed and released to the atmosphere. Decomposed matter (detritus) forms the base of the aquatic and terrestrial food web.

Decomposition requires oxygen and thus reduces the dissolved oxygen content of the water. High rates of decomposition – such as after algae blooms – can reduce water quality and impair aquatic life support.

The values of wetland functions related to biogeochemical cycling and storage include water quality and erosion control.

4.2.1. Nitrogen (N)

The biological and chemical process of nitrification and denitrification in the nitrogen cycle transforms the majority of organic nitrogen entering wetlands, causing between 70% and 90% to be removed.

In aerobic substrates, organic nitrogen may mineralize to ammonium, which plants and microbes can use, adsorb to negatively charged particles (e.g. clay), or diffuse to the surface. As ammonia (NH_3) diffuses to the surface, the bacteria *Nitrosomonas* can oxidize it to nitrite (NO_2). The bacteria *Nitrobacter* in turn oxidizes nitrite to nitrate (NO_3). This process is called nitrification. Conversely, plants or microorganisms can assimilate nitrate, or anaerobic bacteria may reduce it (denitrification) to gaseous nitrogen (N_2) when nitrate diffuses into anoxic (oxygen depleted) water. The gaseous nitrogen volatilizes and the nitrogen is eliminated as a water pollutant. Thus, the alternating reduced and oxidized conditions of wetlands complete the needs of the nitrogen cycle and increase denitrification rates.

4.2.2. Phosphorus (P)

Phosphorus can enter wetlands attached to sediment or in dissolved form. Its removal from water in wetlands occurs through uptake of phosphorus by plants and soil microbes; adsorption by aluminium and iron oxides and hydroxides; precipitation of aluminium, iron, and calcium phosphates; and burial of phosphorus adsorbed to sediments or organic matter. Wetland soils can, however, reach a state of phosphorus saturation, after which phosphorus may be released from the system. Phosphorus is released into surface water as organic matter decomposes.

Dissolved phosphorus is processed by wetland soil microorganisms, plants and geochemical mechanisms. Microbial removal of phosphorus from wetland soil or water is rapid and highly efficient; following cell death, however, the phosphorus is released into the water again. Similarly, for plants, litter decomposition causes a release of phosphorus. Burial of litter in peat can provide long-term removal and storage of phosphorus. Harvesting of plant biomass is needed to maximize biotic phosphorus removal from the wetland system.

4.2.3. Carbon (C)

Wetlands store carbon within peat and soil, and so play an important role within the carbon cycle, particularly given observations of increasing levels of carbon dioxide in the atmosphere and concerns about global warming. When wetlands are drained the oxidizing conditions increase organic matter decomposition, thus increasing the release of carbon dioxide. When wetlands are preserved or restored, the wetlands act as a sink for carbon since organic matter decomposition is stabilized or slowed.

4.2.4. Sulphur (S)

Wetlands are capable of reducing sulphate to sulphide. Sulphide is released to the atmosphere as hydrogen, methyl and dimethyl sulphides or is bound in insoluble complexes with phosphate and metal ions in wetland sediments. Dimethyl sulphide released from wetlands may act as a seed for cloud formation. Sulphate may exist in soils or enter wetlands through tidal flow or atmospheric deposition.

4.2.5. Suspended Solids

Wetlands filter suspended solids from water that comes into contact with wetland vegetation. Stems and leaves cause friction that affects the flow of the water, thus allowing settling of suspended solids and removal of related pollutants from the water column. Wetlands may retain sediment in the peat or permanently as substrate. Sediment deposition varies across individual wetlands and wetland types, as deposition depends upon the rate and type of water flow (channelized or sheet flow), particulate size and vegetated area of the wetland.

4.2.6. Metals

All soils contain at least a low concentration of metals, but in some locations human activities have resulted in metal levels high enough to cause health or ecological risks. Metals may exist in wetland soils or enter wetlands through surface or groundwater flow.

Wetlands can remove metals from surface and groundwater as a result of the presence of clays, humic materials (peats), aluminium, iron and/or calcium. Metals entering wetlands bind to the negatively ionized surface of clay particles, precipitate as inorganic compounds (including metal oxides, hydroxides and carbonates controlled by system pH), interact with humic materials, and adsorb or occlude to precipitated hydrous oxides. Iron hydroxides are particularly important in retaining metals in salt marshes. Wetlands remove more metals from slow-flowing water since there is more time for chemical processes to occur before the water moves out of the area. Burial in the wetland substrate will keep bound metals immobilized. Neutral pH favours metal immobilization in wetlands. With the exception of very low pH peat bogs, as oxidized wetland soils are flooded and reduced, pH converges toward neutrality (6.5 to 7.5), whether the wetland soils were originally acidic or alkaline.

4.3. Wetland Ecology

Wetlands are productive ecosystems. Immense varieties of species of microbes, plants, insects, amphibians, reptiles, birds, fish and other wildlife depend on them in some way. Wetlands with seasonal hydrological pulsing are the most productive.

Wetland plants play an integral role in the ecology of the watershed. They provide breeding and nursery sites, resting areas for migratory species, and refuge from predators. Decomposed plant matter (detritus) released into the water is the source of food for many invertebrates and fish both in the wetland and in associated aquatic systems. Physical and chemical characteristics such as climate, topography, geology, hydrology, and inputs of nutrients and sediments determine the rate of plant growth and reproduction (primary productivity) of wetlands.

The greater the amount of vegetation, the more the wetland vegetation will intercept runoff and be capable of reducing runoff velocity and removing pollutants from the water. Wetland plants also reduce erosion as their roots hold the soil particles of streambanks, shorelines or coastlines.

The inundated or saturated conditions occurring in wetlands limit plant species composition to those that can tolerate such conditions. Beaver, muskrat and alligators create or manipulate their own wetland habitat, which other organisms, such as fish, amphibians, waterfowl, insects and mammals, can then inhabit.

Wetland shape and size affect the habitat of the wildlife community. The shape affects the perimeter–area ratio, which is important for the success of interior and edge species. Shape is also important for movement of animals within the habitat and between habitats. Wetland size is particularly important for larger and wider-ranging animals that use wetlands for food and refuge, such as black bear or moose, since in many regions wetlands may be the only undeveloped and undisturbed areas remaining.

4.4. Wetland Functions

Only recently have scientists begun to understand the importance of the functions that wetlands perform. Far from being useless disease-ridden places, wetlands provide benefits that no other ecosystem can, including natural water quality improvement, flood protection, shoreline erosion control, opportunities for recreation and aesthetic appreciation, community structure and wildlife support, and natural products at reduced costs compared with other alternatives. Protecting wetlands in turn can increase human safety and welfare as well as enhance the productivity of aquatic ecosystems.

4.4.1. Water Quality and Hydrology

Wetlands have important filtering capabilities for intercepting surface water runoff from higher dry land before it reaches open water. As the runoff water passes through, the wetlands retain excess nutrients and some pollutants, and reduce sediment that would otherwise clog waterways and affect fish and amphibian egg development. In performing this filtering function, wetlands offset the costs of wastewater treatment. In addition to improving water quality through filtering, some wetlands maintain streamflow during dry periods, and many replenish groundwater supplies.

4.4.2. Flood Protection

Wetlands function as natural sponges. They trap and slowly release surface water, rain, snowmelt, groundwater and floodwaters. Trees, root mats and other wetland vegetation slow the speed of floodwaters and distribute them over the floodplain. This combined water storage and braking action lowers flood heights and reduces erosion. Wetlands within and downstream of urban areas are particularly valuable, counteracting the greatly increased rate and volume of surface water runoff from pavement and buildings.

The holding capacity of wetlands helps control floods and prevents waterlogging of crops. Preserving and restoring wetlands, together with other water retention measures, can often provide the level of flood control that would otherwise require expensive dredging operations and levees. The bottomland hardwood-riparian wetlands along the Mississippi River once stored significantly more floodwater than they can today because most have been filled or drained.

4.4.3. Shoreline Erosion

The ability of wetlands to control erosion is so valuable that communities in some coastal areas are restoring wetlands to buffer the storm surges from hurricanes and tropical storms. Wetlands at the margins of lakes, rivers, bays and the ocean protect shorelines and stream banks against erosion. Wetland plants hold the soil in place with their roots, absorb the energy of waves, and break up the flow of stream or river currents.

4.4.4. Fish and Wildlife Habitat

Many animals and plants depend on wetlands for survival. Estuarine and marine fish and shellfish, various birds and certain mammals depend on coastal wetlands for survival. Most commercial and game fish breed and raise their young in coastal marshes and estuaries. Menhaden, flounder, sea trout, spot, croaker and striped bass are among the more familiar fish that depend on coastal wetlands. Shrimp, oysters, clams, and blue and Dungeness crabs likewise need these areas for food, shelter and breeding grounds.

For many animals and plants, like wood ducks, muskrat, cattails and swamp rose, inland wetlands are the only places they can live. Beaver may actually create their own wetlands. For others, such as striped bass, peregrine falcon, otter, black bear, raccoon and deer, wetlands provide important food, water or shelter. Many breeding bird populations – including ducks, geese, woodpeckers, hawks, wading birds and many songbirds – feed, nest and raise their young in wetlands. Migratory waterfowl use coastal and inland wetlands as resting, feeding, breeding or nesting grounds for at least part of the year. Indeed, an international agreement to protect wetlands of international importance was developed because some species of migratory birds are completely dependent on certain wetlands and would become extinct if those wetlands were destroyed.

4.4.5. Natural Products

We use a wealth of natural products from wetlands, including fish and shellfish, blueberries, cranberries, timber and wild rice, as well as medicines that are derived from wetland soils and plants. Many fishing and shellfishing industries harvest wetland-dependent species. In the southeast part of the United States, for example, nearly all the commercial catch and over half of the recreational harvest consists of fish and shellfish that depend on the estuary-coastal wetland system. Wetlands are habitats for fur-pelted animals like muskrat, beaver and mink, as well as reptiles such as alligators.

4.4.6. Recreation and Aesthetics

Wetlands have recreational, historical, scientific and cultural value. More than half of all US adults hunt, fish, go birdwatching or photograph wildlife. Painters and writers continue to capture the beauty of wetlands on canvas and paper, or through cameras, and video and sound recorders. Others appreciate these wonderlands through hiking, boating and other recreational activities. Almost everyone likes being on or near the water; part of the enjoyment is the fascinating variety of lifeforms.

5. Estuaries

Estuaries are places where freshwater mixes with saltwater under the influence of tides, creating a unique environment supporting a rich and diverse ecosystem.

Estuaries are capable of gathering and holding an abundance of life-giving nutrients from the land and from the ocean. They are also important sites for human economic and recreational activities. An estuary can provide a laboratory for lessons in biology, geology, chemistry, physics and social issues.

Estuaries are partially enclosed bodies of water formed where freshwaters from rivers and streams flow into and mix with the saline seawater. They and the lands surrounding them are places of transition from land to sea, and from fresh to saltwater. Although influenced by the tides, they are generally protected from the full force of ocean waves, winds and storms by the reefs, barrier islands or fingers of land, mud or sand that define their seaward boundaries.

Estuarine geometry can vary substantially, and the physical characteristics of estuaries affect the distribution of their constituents. The shape and geomorphology of the estuary influence the flows, circulation and mixing of the waters. The flow pattern and the density structure in an estuary govern the advective transport and diffusion/dispersion characteristics that determine the fate and distribution of waterborne constituents.

The word *estuary* comes from the Latin 'aestus', meaning tide. Traditionally, the upstream limit of an estuary is defined in terms of the limit of penetration of saltwater. Salt concentrations move upstream under the influence of the ocean tide. A commonly used definition is that of Pritchard (1952), who defined an estuary as 'a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage'.

A broader definition of an estuary would take into account the diversity and spatial variability of its fauna and flora. Hutchings and Collett (1977) define estuaries as the tidal portions of river mouths, bays and coastal lagoons, irrespective of whether they are dominated by hypersaline, marine or freshwater conditions. Included in this definition are inter-tidal wetlands, where water levels can vary in response to the tidal levels of the adjacent waterway, together with perched freshwater swamps, as well as coastal lagoons that are intermittently connected to the ocean.

Perched freshwater swamps, or swamps located above the regional water table, can occur in the lower catchment areas of an estuary. Although tides or ocean salinity does not affect them, they can form an important component of the estuarine habitat. For this reason, such swamps need to be included in estuarine management plans and policies.

5.1. Types of Estuaries

Every estuary is unique, yet all share certain features. Some are similar enough to be grouped or classified according to their shared characteristics. Others are typical of specific regions. All are greatly affected by geology, climate and many other factors, including the ever-growing human population.

Depending on their geological characteristics, estuaries can be classified as:

- *Coastal plain estuary* (*or drowned river valley*). These are commonly found along coastlines that have relatively wide coastal plains. They were created by the gradual rise in sea level following the last glacial period, some 10,000 years ago. Usually, a stretch of the freshwater river is subject to tidal oscillations. Typically, the estuary is funnel-shaped, widening gradually in the downstream direction, often with inter-tidal mud flats. Sometimes a large delta system has formed with many natural channels. Chesapeake Bay is the largest estuary of this type of in the United States.
- *Fjord-type estuary* (*formed by a glacier*). These estuaries generally have U-shaped cross sections with steep sides and are often quite deep (300 or 400 m). They are common in the Northern Hemisphere above 45 degrees latitude. In North America they are most spectacular along the coast of Alaska and British Columbia.
- *Bar-built estuary or lagoon*. These are formed when offshore barrier sand islands and sand pits become higher than sea level and extend between headlands in a chain, broken by one or more inlets. Lagoons are usually situated parallel to the coastline. Many have narrow outlets to the sea and minimal freshwater inflow, often creating higher salinity levels than in coastal-plain and other estuaries. In North America, lagoons occur mainly along the Gulf Coast. Smaller lagoons occur along the West Coast.
- *Estuaries produced by tectonic processes*. Estuaries created by processes such as landslides, faulting and volcanic eruptions are found along coasts where such

activity is or has been common, such as the Pacific Coast of North America. These estuaries vary greatly and often share characteristics with other types. The largest in the United States is San Francisco Bay.

Any existing estuary can be a 'composite estuary' evolving from an overlap of two or more of these basic types.

Estuaries can also be classified on the basis of stratification and circulation:

- A *salt-wedge* estuary is highly stratified. Saltwater moves into it in the shape of a wedge, with freshwater flowing over it. The velocity of the freshwater outflow is usually greater than that of the saltwater inflow. This keeps the saltwater from extending very far up the estuary. The Mississippi River Estuary is an example of this type, where the difference in water level between the high and low tides (the tidal range) on the seaward side of the estuary is small and incapable of mixing the stratified layers.
- The *vertically homogenous* or well-mixed estuary is characterized by low inflow of freshwater and large tidal ranges. In such estuaries, saltwater and freshwater tend to mix vertically, and sometimes laterally as well.
- *Intermediate* estuaries are partly mixed. They exhibit circulation patterns that are somewhere between those of the salt-wedge and vertically homogenous estuaries. This type of estuary, typical along the US East Coast, has a moderate inflow of freshwater and moderate-to-large tidal range.

Estuaries area also classified based on their circulation – the interaction of tidal currents and river flow (Bowden, 1967):

- A salt wedge estuary has only a small amount of friction between the layers. The steep density gradient at the interface reduces the turbulence and mixing to a low level. The effect of the Coriolis force causes the lateral sloping of the interface downward to the right in the Northern Hemisphere when looking towards the sea.
- A vertically homogeneous estuary can exhibit lateral variation due to Coriolis force in wide estuaries, or be laterally homogeneous where the ratio of width to depth is relatively small. Coriolis force causes a net seaward flow of lower-salinity water on the right hand of the estuary, and a compensating flow of higher-salinity water on the left-hand side. In this sequence, the tidal currents are stronger in relation to the river flow.
- In a two-layer flow with entrainment, the entrainment is due to breaking internal waves. Many fjords have this type of circulation.
- In a two-layer flow with vertical mixing, the volume of water involved in this type of circulation may be many times the river discharge. Examples include the Tees and Thames estuaries in the UK.

Estuaries are constantly affected by tidal and wave action, prevailing and changing winds, local and distant weather systems, and variations of rainfall runoff and river discharge.

5.2. Boundaries of an Estuary

With some exceptions, such as those found in the Mediterranean Sea, tidal motions are significant features in estuaries. The upstream boundary or head of an estuary is the limit of tidal influence. The tidal limit can be a considerable distance upstream from the salinity limit. The actual limit of tidal influence varies with time, depending upon freshwater flows and the natural variability of tides. It can be difficult to determine the tidal limit by mere observation. Towards the limit of tidal influence, flood flows may persist for as little as an hour or less, and may be so small as to go unnoticed.

As well as short-term cyclical changes in response to the changing ocean tides, there may be long-term variations in the upstream boundary of an estuary due to both natural processes and artificial disturbance. The downstream boundary is not always obvious, but it corresponds to the seaward limit of the entrance bar in most situations.

The lateral boundaries of an estuary are often defined in ecological rather than hydraulic terms. The shallow and inter-tidal margins of an estuary support the diversity and productivity of marine life, such as sea-grass meadows, mangrove forests and saltmarshes, all generating large amounts of organic detritus that form the foundation of the estuarine food chain.

The lateral extent of an estuary includes all wetlands – salt, brackish and fresh – that interact with tidal and flood flows. They also include those marshes that are inundated only during extreme tides or flood events.

5.3. Upstream Catchment Areas

An estuary acts as a funnel to convey freshwater runoff from the land into coastal waters. Catchment activities can affect the volume and quality of this runoff. Floodwaters and stormwater runoff often contain significant quantities of suspended solids, natural and artificial nutrients, pesticides and other constituents, some of which can be detrimental to estuarine ecosystems.

Upstream catchment activities are the single most important factor in determining the nutrient balance and water quality of estuaries. The impact of external activities occurring beyond the strictly defined estuarine limits points to the need for a *total catchment management* approach in managing estuaries. What we do upstream affects what happens downstream, including, for most rivers, the estuary.

5.4. Water Movement

Water moves along an estuary under the influence of two primary forcing mechanisms: freshwater inflows from rivers and the regular tidal movement of seawater into and out of the estuary. In addition, differences in tides, winds and salinity densities within the estuary generate secondary currents that, while of low velocity, can be significant with respect to mixing and sediment transport.

Freshwater inflows fluctuate in a more or less random fashion in response to surface runoff from tributary catchments. The construction of major dams in upstream catchment areas reduces both the volume of freshwater runoff and the freshwater flushing of estuaries. In times of drought, freshwater inflows may be absent, or may be mainly the discharge of sewage effluent and other wastewaters.

Freshwater inflows result in a net seaward excursion of water particles over each tidal cycle, and thus promote estuary flushing.

The movement of seawater in and out of an estuary is predominantly influenced by the tides. Freshwater effects are generally small (but often significant with respect to water quality), except during floods.

Coastal water levels fluctuate in a regular and predictable fashion in response to gravitational effects, primarily of the moon and sun, on the oceans of the earth. The tidal range varies from one tidal cycle to another in response to the changing relative positions of these celestial bodies. In response to the monthly orbit of the moon around the earth, the tidal range undergoes a regular fourteen-day cycle, increasing to a maximum over a week (spring tides) and then decreasing to a minimum over the following week (neap tides). Solstice tides, or king tides occur in June and December of each year, when the sun is directly over the Tropics of Cancer and Capricorn respectively.

Tides along many coastlines are semi-diurnal in nature; that is, high water and low water occur about twice daily (the actual period of a tidal cycle is about 12.5 hours). They are sinusoidal in shape and have a pronounced diurnal inequality (successive high tides differ markedly).

The tidal rise and fall of ocean water levels propagates along an estuary as a wave. The speed of travel or celerity of this wave – the speed at which high water and low water travel upstream from the estuary entrance – varies with water depth: the deeper the water, the faster the wave celerity. The propagation of the tide along an estuary is affected by the geometry of its bed. Tidal propagation in tidal rivers is very sensitive to water depths. In certain estuaries, the ocean tidal range is increased in upstream reaches of the estuary because of its geometry. The celerity of the flood tide is higher than that of the ebb tide.

5.4.1. Ebb and Flood Tides

The vertical rise and fall of tides (Figure A.30) produce horizontal flows in the form of tidal currents. The incoming or rising tide is traditionally referred to as the flood tide because it floods the channel. The outgoing tide is referred to as the ebb tide. The strength of the ebb and flood tide velocities varies diurnally and over spring–neap cycles in exactly the same way as tidal water levels do. Spring tides produce the fastest tidal currents. Depending on the tidal range, entrance characteristics and the depth of the estuary, tidal currents can have velocities of up to a metre a second.

If the tidal range is appreciable compared to the mean depth of the estuary, the speed of propagation of the tide at high water will be significantly faster than at

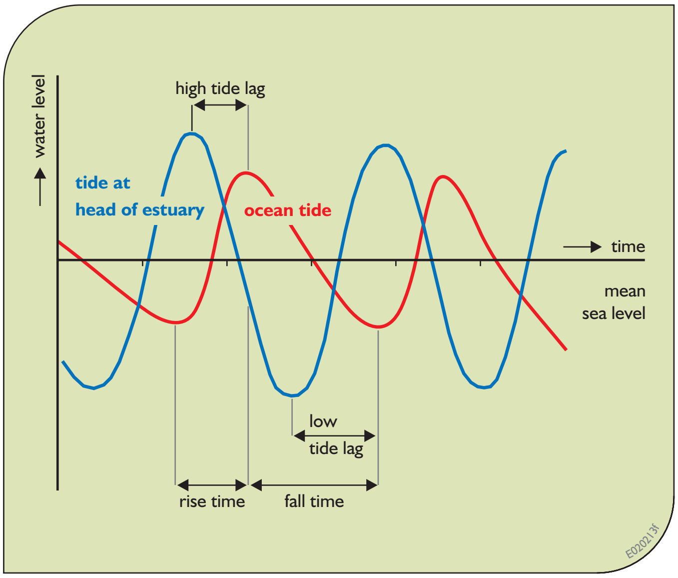

Figure A.30. Tidal characteristics at the entrance and head of a tidal river.

low water. This causes the shape of the tidal wave to become progressively more distorted as it moves landward. This tidal distortion results in a saw-tooth tide curve, in which the rise of the tide is noticeably faster than its fall. As a consequence, peak flood tide velocities are generally greater than peak ebb tide velocities. This is of significance with respect to sediment transport.

The period of quiet water when the tide reverses from flood to ebb or vice versa is referred to as slack water. High-water slack is the name given to the tide change from flood to ebb; low-water slack refers to the tide change from ebb to flood. The duration of slack water varies from one estuary to another and can last from twenty minutes to almost an hour.

5.4.2. Tidal Excursion

The total distance travelled by a water particle from low-water slack to high-water slack and vice versa is referred to as the tidal excursion. This is the maximum distance travelled by a water particle during the rising or falling limb of the tide.

Tidal excursion is not to be confused with the distance travelled by the tide wave itself (e.g. high water) that propagates from the ocean to the end of the estuary each tide cycle.

Freshwater inflows impose a net seaward movement on water particles over a tide cycle. In these circumstances, the ebb tide excursion is greater than the flood tide excursion. This is illustrated in Figure A.31, which also shows the net effect of oscillatory tidal flows and seaward-draining freshwater flows in flushing a parcel of water out to sea.

5.4.3. Tidal Prism

The total volume of water moving past a fixed cross section of the estuary during each flood tide or ebb tide (i.e. slack water to slack water) is referred to as the tidal prism. The larger the tidal range within the estuary and the greater the dimensions of the estuary, the larger is the tidal prism. On average, the ebb and flood tidal prisms are equal.

The size of the tidal prism is not an indication of the amount of flushing. The movement of water contained in the tidal prism is largely oscillatory, as depicted in Figure A.31. The net seaward flushing action over a tidal cycle results from two processes: freshwater advection and longitudinal dispersion. Freshwater advection is the net seaward displacement caused by Freshwater. Freshwater longitudinal dispersion results mainly from the tides.

5.4.4. Tidal Pumping

The higher celerity of the flood tide compared to the ebb tide results in a tendency for greater upstream movement of water on the flood tide compared to downstream movement on the ebb tide. This leads to a dynamic trapping of water in the upper reaches of the estuary. This effect is sometimes referred to as tidal pumping: tidal distortion results in the tide pumping water upstream.

In shallow estuaries, tidal pumping can affect the distribution of dissolved pollutants along an estuary.

5.4.5. Gravitational Circulation

The presence of salt in an estuary produces a longitudinal density gradient, with water densities around the mouth of the estuary being greater (because of higher salt concentrations) than densities around the head of the estuary. This results in the enhancement of flood-tide velocities near the bed and ebb-tide velocities near the surface. When averaged over a tidal cycle, this behaviour leads to

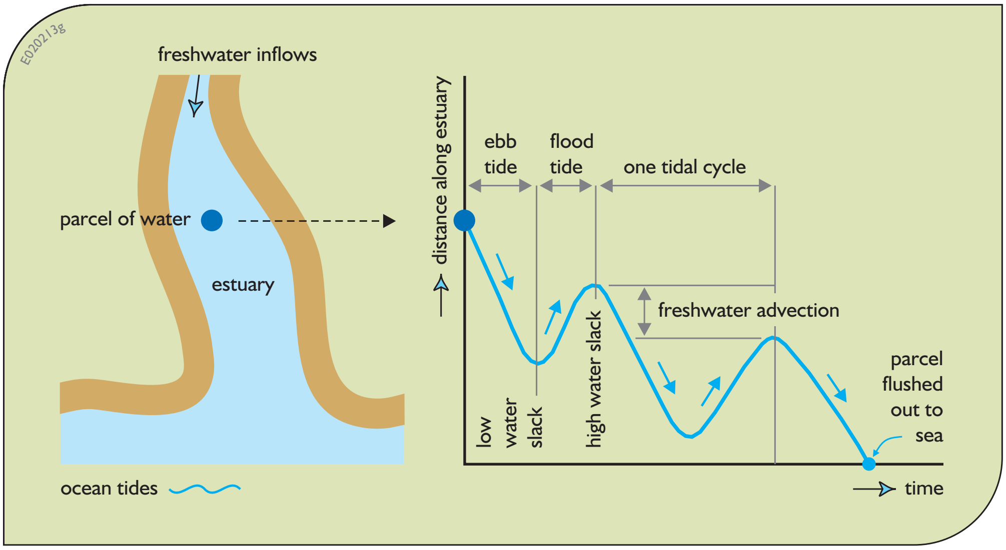

Figure A.31. Movement of a 'parcel' of water down an estuary.

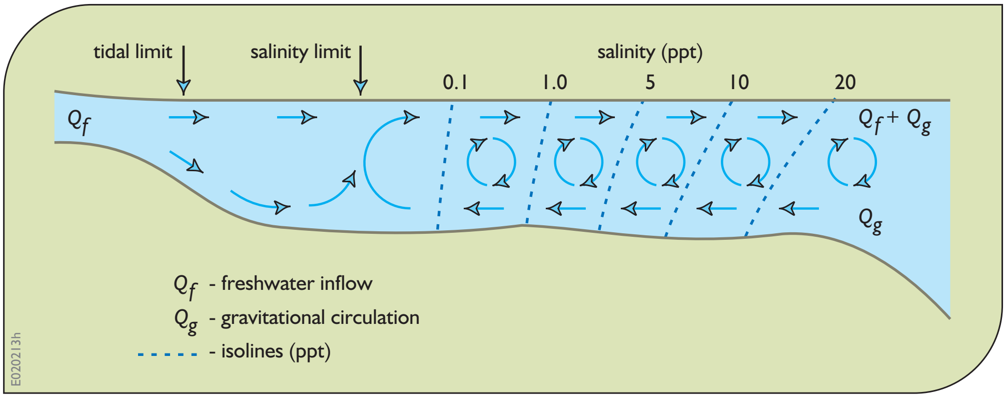

Figure A.32. Gravitational circulation in a partially mixed estuary.

residual currents, in which saline water flows upstream along the bottom of the estuary and less salty, even fresh water, flows seawards near the surface (see Figure A.32). This pattern of residual flows is referred to as gravitational circulation (it is driven by the gravitational forces resulting from density differences). Gravitation circulation can give rise to discharges considerably greater than freshwater inflows. Gravitational circulation is an important mechanism of upstream sediment transport and the longitudinal dispersion of salt in an estuary.

5.4.6. Wind-Driven Currents

Wind shear at the water surface produces surface currents, counterbalancing currents at the bottom of the water column, and large-scale lateral circulation. Wind speeds up to about 6 to 7 m/sec are the most effective in moving surface waters. Wind-driven surface currents have speeds of about 2% of the wind speed. Wind-driven currents are a major mechanism in the transport and distribution of floating pollutants such as oil.

In sluggish tidal systems or bays, where surface tidal flows are weak, wind-driven currents can be among the main agents leading to effective water movement and mixing within the main water body. When a constant wind blows over a basin of variable depth, a laterally varying surface current is induced, flowing with the wind in shallow areas and as a return flow against the wind in deeper areas.

5.5. Mixing Processes

Parcels of water mix as they move along the estuary under the influence of freshwater flows, tidal flows and secondary currents. Mixing not only involves an exchange of water mass, but also of any substance dissolved in it, such as salts and various pollutants. Mixing processes affect the distribution of salinity and water quality constituents throughout the estuary.

5.5.1. Advection and Dispersion

Advective and dispersive transport are the major processes by which dissolved matter is distributed throughout an estuary. As water flows along an estuary it transports dissolved matter with it. This is advective transport. During this process, water mixes with neighbouring parcels of water. This mixing, or dispersive transport, leads to a net transport of dissolved materials from regions of high concentration to regions of lower concentration.

The mixing of parcels of water is principally caused by lateral and vertical variations in velocity along an estuary. These variations create velocity shear. Velocity variations result in faster parcels of water – together with their dissolved loads – moving ahead of their slower neighbours, as depicted in Figure A.33. Turbulence and eddies generated by the velocity shear between neighbouring parcels result in the interchange of water and dissolved matter between parcels.

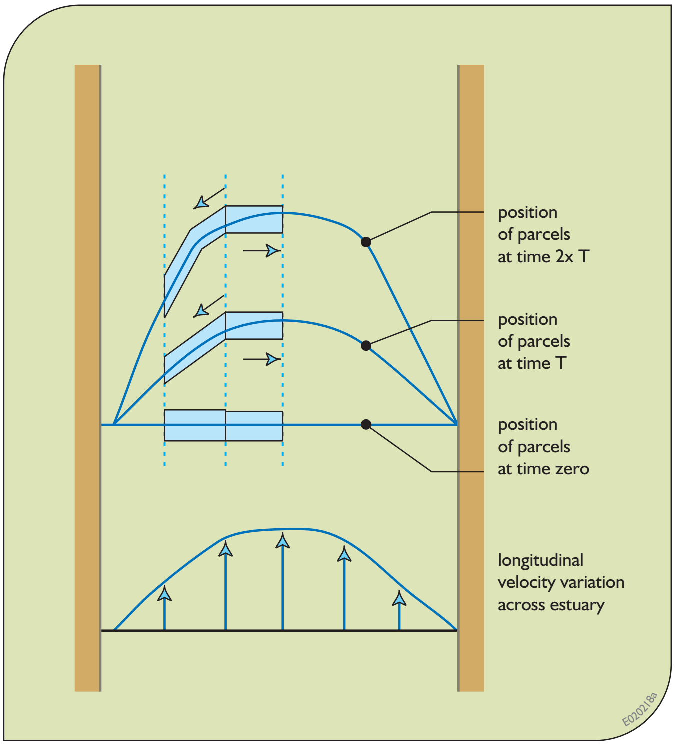

Figure A.33. Mixing caused by the lateral variation of velocity across an estuary.

5.5.2. Mixing

Mixing occurs in all three directions – vertically laterally and longitudinally. The principal mechanism of vertical mixing is the velocity shear caused by flow moving across the bed of the estuary. The surface and mid-depth flow velocities are faster than bed-flow velocities. This results in turbulence, principally at the bed, which promotes the mixing of overlying waters. Vertical mixing is responsible for well-mixed salinity regimes.

The major mechanisms promoting the mixing of waters laterally across an estuary are the velocity shear associated with lateral velocity gradients, wind shear, lateral tidal flows, large-scale eddies generated by obstructions, and bends and meanders in the alignment of major channels.

Figure A.33 shows the lateral exchange of parcels of water associated with the lateral variation of longitudinal velocities across the estuary. Lateral variations in velocity are caused by the presence of the banks of the estuary and changes in water depth. Deeper waters flow faster than shallow waters. This lateral exchange promotes mixing across the estuary.

Wind shear and lateral tidal flows (such as the filling of inter-tidal areas on the flood tide) both result in the advection of water across an estuary and associated mixing. The presence of bends and meanders also results in water flowing from one side of a channel to the other, and associated mixing across the channel.

Obstructions such as rock bars and shoals also promote the flow of water across an estuary, both by the advection associated with redirected flows and by the dispersion associated with lateral shear.

Large-scale boundary effects, tidal trapping, tidal loops and interconnections between tidal systems, and gravitational circulation are among a number of factors that promote longitudinal mixing. Large-scale boundary effects relate to the mixing caused by the presence of bays and channels along an estuary. Waters are temporarily stored in these areas on the rising tide and released when it falls. This separation of the trapped waters from other waters moving along the estuary facilitates mixing by velocity shear and advective transport.

The presence of shoals generates strong velocity shear between fast-moving main channel flows and the slow-moving waters that move in and out of shoal areas on the rising and falling tide. This behaviour leads to tidal trapping, whereby a discrete body of water is separated and trapped over shoal areas on the flood tide, to be released on the ebb. This behaviour facilitates mixing by velocity shear and advective transport, supplementing that resulting from large-scale boundary effects.

Finally, the presence of tidal loops in a large delta or the interconnection of two tidal systems can create a complicated pattern of residual flows that further enhances advective and dispersive transport along the estuary. To summarize, mixing will be greatest in those estuaries where lateral and vertical velocity gradients are greatest, that is, in estuaries where deep channels thread their way through shallow flats, where there are extensive shoals and peripheral bays and channels, and where tidal flows are fast.

5.6. Salinity Movement

Seawater consists of a dilute solution of a mixture of salts. The term salinity refers to the total salt concentration. Seawater has a worldwide average salt concentration of about 35 kg/m^3 or 35 parts per thousand (ppt). Saline coastal waters are carried into an estuary by the tides; freshwater inflows tend to wash the saltwater back out to sea. Tidal flows are very effective in moving salinity upstream. This is seen in the relatively quick migration of salinity upstream in an estuary after a major flood has washed it downstream. The balance between the landward transport of salt by tidal processes and its seaward return by freshwater discharges determines the limit of salinity intrusion along an estuary.

Salt and other dissolved substances are transported along an estuary by the longitudinal advection associated with large-scale water movements and secondary currents, and by the longitudinal dispersion associated with velocity shear. Freshwater inflow is the major factor affecting the limit of saline intrusion along an estuary. Salt will not penetrate far along channels with a net seaward residual velocity in excess of 0.1 m/sec.

5.6.1. Mixing of Salt- and Freshwaters

The density of seawater is greater than that of freshwater and varies depending on both salinity and temperature. At a temperature of 20 °C, seawater has a density of about 1,025 kg/m^3, whereas freshwater at that temperature has a density of 1,000 kg/m^3. Although the difference in density is relatively small, it still affects estuarine circulation.

Because of its lower density, freshwater tends to float on top of the seawater (stratification). Turbulence generated by the movement of the water over the bed of an estuary causes vertical mixing, which tends to break down any saline–freshwater stratification. The faster the water moves, the greater its turbulence and resultant mixing. High tidal velocities produce strong vertical mixing, resulting in little variation in salinity from the top to the bottom of the water column. Low tidal velocities are insufficient to cause complete vertical mixing and stratified conditions can develop (i.e. bottom salinity concentrations are greater than surface salinity concentrations).

5.6.2. Salinity Regimes

In well-mixed estuaries, the salinity distribution is almost uniform with depth. In partially mixed estuaries, the salinity varies continuously through the depth of the water column, with no evidence of a marked interface between the upper and lower layers. The salinity can vary over the depth by as little as 1 ppt or as much as 10 ppt.

Stratified conditions are characterized by an abrupt increase in salinity over the water depth. In the absence of significant tidal velocities, vertical mixing in an estuary is weak. This allows the saltwater to move into the estuary as an arrested salt wedge that can penetrate a long distance into a deep estuary.

The freshwater overlying the wedge tends to entrain saltwater as it moves seaward, thereby becoming more brackish as it approaches the estuary mouth. These conditions are shown in Figure A.34.

5.6.3. Variations due to Freshwater Flow

If there is considerable variation in freshwater inflows over time, the estuaries can display all of the foregoing salinity regimes (shown in Figure A.34) at different times. During periods of extended dry weather, when freshwater flows are small, estuaries tend to be well mixed. When freshwater inflows to estuaries are low, the salinity of water in the estuary may exceed the salinity of

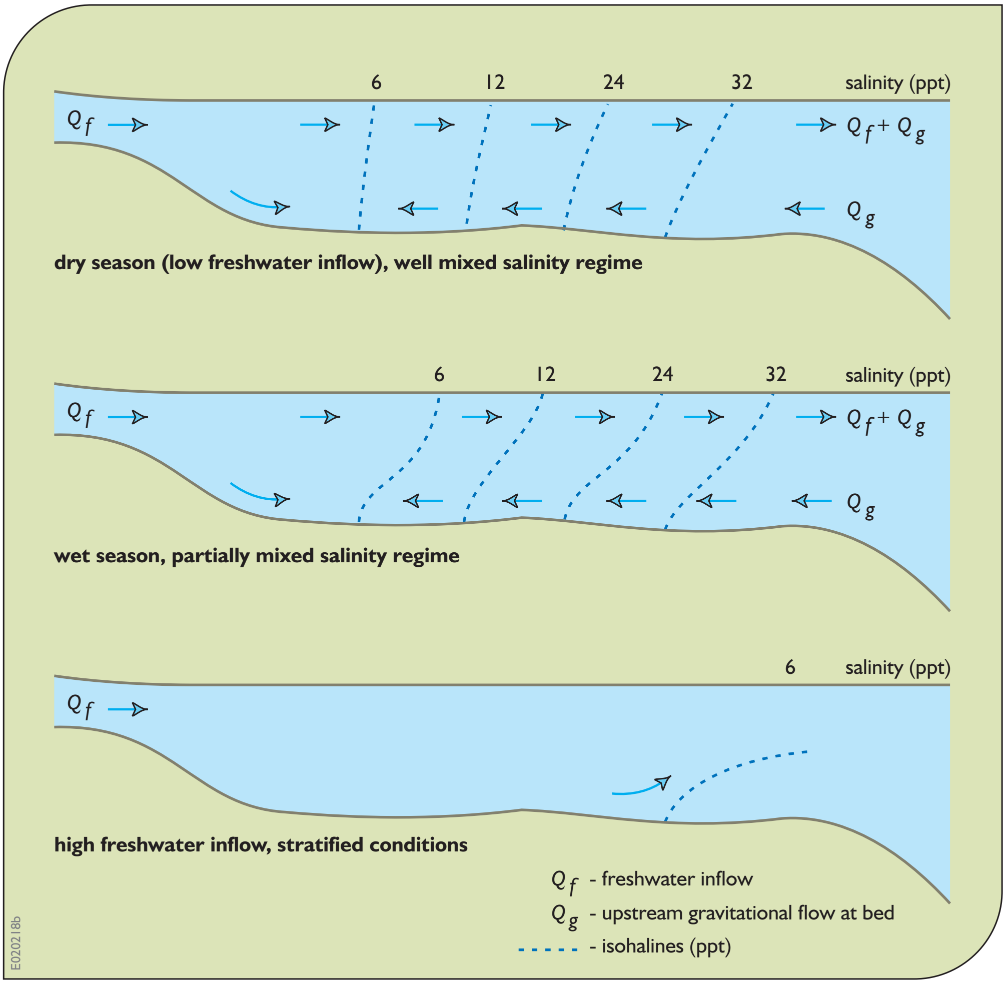

Figure A.34. Possible salinity regimes in tidal rivers.

the open ocean (hyper-saline conditions). During periods of wet weather, partially mixed conditions prevail. Under full flood flows, stratified conditions occur in entrance reaches and most of the salt may be washed out to sea.

5.7. Sediment Movement

Sediment is a major component of most estuaries. Its sources, movements and impacts are numerous.

5.7.1. Sources of Sediment

Different types of sediment are delivered to an estuary by a variety of sources, as illustrated in Figure A.35. Riverbank erosion and general catchment runoff produce quantities of sand, silt and clay. Catchment runoff also delivers organic matter to the river/estuary. Littoral processes in coastal waters can supply large quantities of sand to an estuary. Wind action on dunes and inter-tidal sandbanks carry fine sand into an estuary.

5.7.2. Factors Affecting Sediment Movement

The currents caused by freshwater inflows and tidal behaviour are the main mechanisms moving sediment in estuaries. The faster these currents, the greater will be the shear stress and turbulence generated at the bed, and the greater will be the movement of sediment by bedload and suspended load transport.

Sediment movement depends on flow, turbulence and the physical characteristics of the sediment particles. Sediment transported in water will settle at times or places of low wave or tidal activity. The rate of settling depends upon the grain size of sands and upon the mineralogy and chemistry of muds.

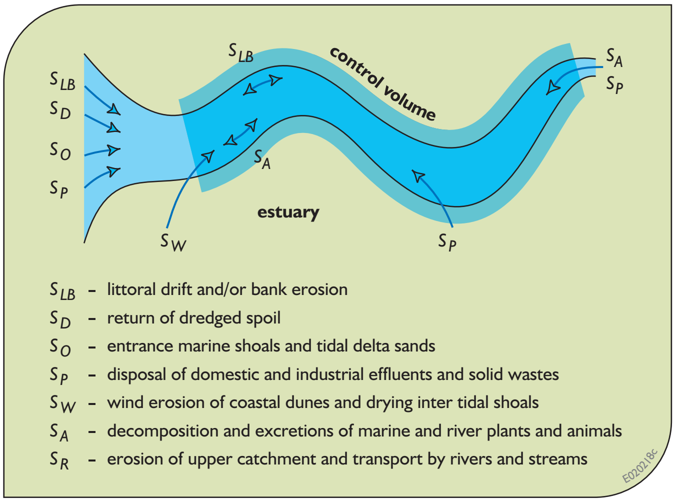

Figure A.35. Sources of sediment in an estuary (McDowell and O'Connor, 1977).

Sediment on the bed will be eroded and transported when the shear stress exerted on the bed by waves, tides and freshwater action, acting either alone or together, exceeds a critical minimum value. The critical shear stress also varies according to sediment size, mineralogy and chemistry.

If sediment is deposited in locations where the critical shear stress is not exceeded, or is exceeded only infrequently, then the sediment will slowly consolidate, increasing in both density and strength. As bed density increases, the stress threshold for erosion will increase, and the sediment deposit will become more stable and less likely to be eroded by natural forces.

The difference between peak flood flow and peak ebb flow velocities (tidal distortion) and gravitational circulation facilitate a net upstream movement of suspended solids, in other words, a residual suspended load flux. Because of tidal distortion, the duration of high-water slack is different from low-water slack, thereby generating differences in the slack water settling opportunity for suspended particles. This, coupled with differences in current behaviour around the two slacks, can impart a net displacement to suspended sediment each tide cycle.

Bedload transport is the principal means by which sand is moved along the estuaries. Suspended load transport of sands occurs usually in the immediate vicinity of estuary entrances, where high velocities (greater than 1 m/s) and wave action promote the suspension of sand grains.

Bedload transport is quite sensitive to small changes in velocity, such as those brought about by tidal distortion and gravitational circulation. These two mechanisms generate residual bedload flux in the upstream direction. Together, these two processes result in a net upstream transport of marine sand that forms shoals and deltas in lower estuarine reaches.

Freshwater flows during large floods can transport sand downstream at very high rates, as evidenced by the substantial scouring of shallow sand shoals that tends to occur during floods. The sand transported downstream by freshwater flows is deposited on the seaward face of the entrance bar (the ebb terminal lobe of Figure A.36). After the flood dissipates, this sand is reworked by the action of waves and nearshore currents and is returned to the shoreline over a period of many months.

The action of wind on exposed sand dunes can transport considerable quantities of sand into an estuary. Transport of sand by wind is one of the dominant factors in the sediment budget of exposed entrances and may be the principal reason for the tendency of such entrances to close.

5.7.3. Wind Effects

Some transport of sand grains from inter-tidal sand shoals exposed by the ebb tide also occurs through wind action. Wind-generated waves can have a significant effect on sediment production and movement along estuarine foreshores.

Within the relatively narrow confines of river estuaries, wind-generated waves are small and of short wave length (typically, the significant wave height is 0.3 m or less). Nevertheless, these waves can cause extensive riverbank erosion when the dominant wind direction coincides with a long, straight and wide stretch of the estuary.

Wind waves are often the dominant transport mechanism along the foreshores of tidal lakes (tidal and freshwater velocities in the body of the lake are generally low). Inter-tidal sand and mudflats around the peripheries of tidal lakes are formed as a result of wind waves and wind induced currents.

5.7.4. Ocean Waves and Entrance Effects

The movement of sand into and out of the entrance of an estuary is a complex phenomenon because of the interaction of tidal, wave and freshwater transport processes. Figure A.36 depicts the principal sediment pathways around an estuary entrance.

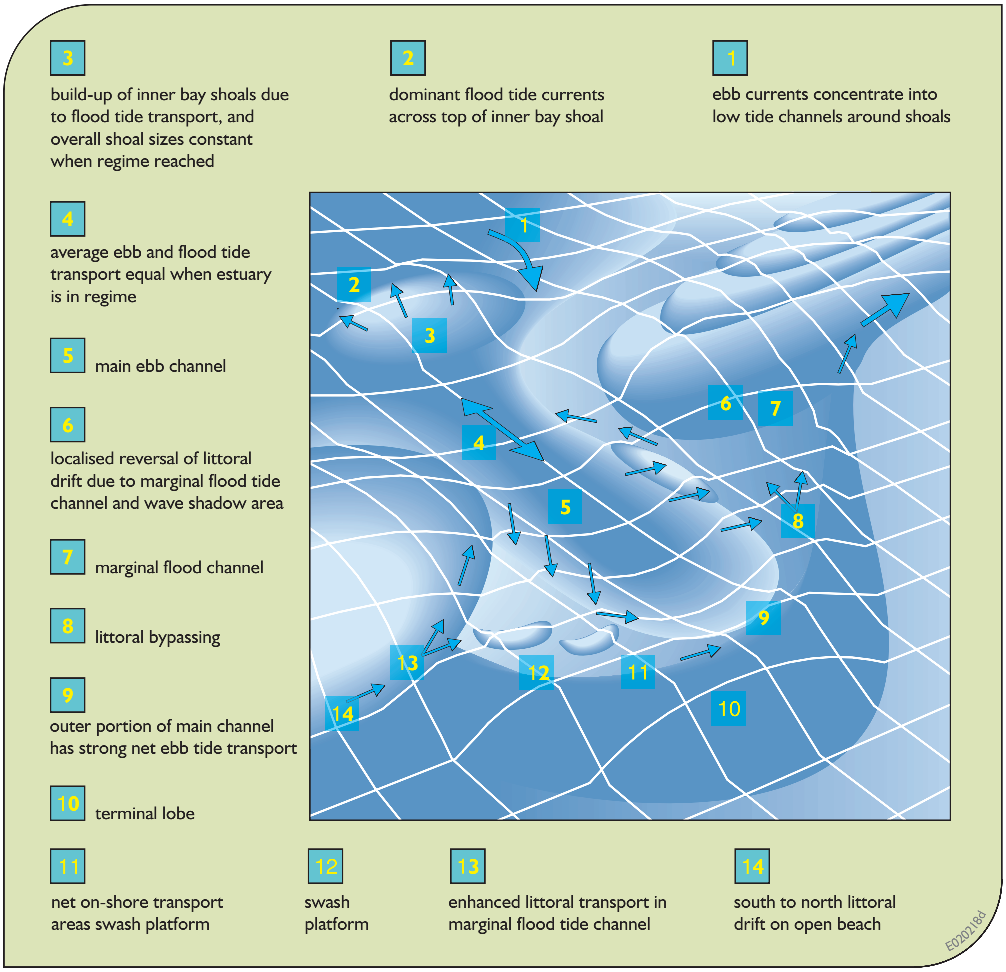

Figure A.36. Sediment pathways at an estuary entrance.

Waves breaking on the entrance bar bring into suspension considerable volumes of sand that can be carried into the estuary on the flood tide. Much of this sand is usually flushed back out of the estuary on the ebb tide, but a small amount may be deposited in the estuary, where it will be transported upstream by the net flood-tide transport caused by the tidal distortion.

Most of the sand transported out of the entrance by floods will be deposited on or near the entrance bar, from where it will be carried to the updrift coastline by a process known as littoral bypassing (see Figure A.36). In addition to their stirring up sediments from the entrance bar and promoting suspended sediment transport, the significance of ocean waves to estuarine sediment transport depends upon the entrance conditions.

Where there is a well-developed offshore bar, ocean waves will break on it and little wave energy will penetrate the lower reaches of the estuary. In these circumstances, ocean waves will have little effect on sediment transport within an estuary.

In contrast, ocean waves can readily penetrate the lower reaches of drowned river valley estuaries, where they combine with tidal flows to produce a relatively complex pattern of sediment movement. In some tidal lakes and rivers with relatively wide mouths, tidal sediment transport is enhanced by the penetration of waves through the entrance.

5.7.5. Movement of Muds

Muds are cohesive materials, and hence the processes of settling, consolidation and resistance to erosion are dependent upon inter-particle bonding and the hydrodynamic environment.

Mud particles and aggregations (flocs) of mud particles have small settling velocities. Turbulent mixing keeps mud particles in suspension throughout the tide, except at slack water when a concentrated layer of mud forms near the estuary bed. Tidal distortion and gravitational circulation result in a net upstream movement of mud particles that are deposited around the limit of the gravitational circulation current.

Muds will remain suspended in a body of moving water when the vertical mixing due to turbulence is equal to or greater than the rate of settling of individual particles. As velocities decrease, so does the vertical mixing and deposition will increase.

The settling velocity of muddy sediment is dependent upon its concentration. At high concentrations, more collisions occur between particles and the resulting flocs are larger and settle faster than the smaller particles. At low concentrations, there is little or no interaction between particles. In these cases, the settling velocity tends to be constant. At very high concentrations, the particles actively interfere with each other and hinder settling.

Like any sediments, muds begin to erode when the shear stress imposed by water movement is equal to the shear strength of the surface layer of mud. The resistance of new mud deposits to subsequent erosion increases with time. As consolidation occurs the cohesion among individual particles and flocs increases, and hence their resistance to erosion increases. Armouring also increases with time and renders the deposit more erosion resistant.

In some cases, the strength obtained through consolidation and armouring will be insufficient to resist the erosive forces of the next half-tide cycle. In these circumstances, all the material will be resuspended. In other cases, some of the deposit will be eroded and the remainder will be largely undisturbed. The residual deposit may then remain largely undisturbed until the next spring tide cycle, when it may or may not have gained sufficient strength to resist the stronger tidal currents.

The pattern of mud deposition within an estuary varies seasonally and spatially in response to the variable nature of the salinity limit. Mud particles brought into suspension are transported upstream by the gravitational circulation. This produces a turbidity maximum near the upstream limit of the circulation, leading to increased deposition of muds at slack water. In other words, the gravitational circulation leads to a trapping of muds in the estuary. The location of the zone of maximum deposition will vary with freshwater flow and the resulting pattern of salt intrusion.

The mud trapping efficiency of an estuary drops off quickly as freshwater flows increase. During major floods, the high turbulence and flushing of the flood flows is usually sufficient to keep the very high suspended load in suspension and flush it entirely out to sea. Tidal lakes, however, act as settling basins, and mud accumulates on the lake bed after each flood.

Drowned river valley estuaries and artificially deepened port areas in estuaries trap most of the mud brought into the estuary by small floods. This can be a major concern for the maintenance of shipping channels. However, during major floods most of the mud is discharged to the ocean. This is just as well, otherwise port areas might be buried in mud by a single major flood event.

5.7.6. Estuarine Turbidity Maximum

Most estuaries contain a specific region having an extra high concentration of suspended particles. The turbulent area in the river where the tidal forces interact with the fast-flowing fresh river waters creates a 'cloud' of suspended particulate matter (SPM): a mix of inorganic sediment, organic detritus and living organisms such as algae and zooplankton. This region is called the estuarine turbidity maximum or ETM. The ETM is very important for supporting biogeochemical, microbial and ecological processes that sustain a dominant pathway in the estuary's food web.

The turbidity maximum generally occurs near the upstream limits of the salinity intrusion due to particle trapping caused by circulation phenomena induced by tides and density-driven (gravitational) currents. Tidal shear also traps particulate matter. The turbidity maximum varies in location, spatial extent and particulate matter concentration, depending on the tidal and river flow conditions.

5.7.7. Biological Effects

Estuarine organisms influence both the settling and resuspension of sediments. Sea-grass beds reduce current velocities and dampen wave action near the bed, thereby increasing the settling of fine material. Filter feeders such as oysters ingest considerable amounts of fine suspended organic and mineral particulate matter that would otherwise remain in suspension. They eject waste in the form of pellets, which settle to the bottom. The activities of some other animals have the opposite effect. The feeding behaviour of many fish, birds and invertebrates disturbs bed sediments and resuspends fine particles, thereby increasing water turbidity.

The physical properties and stability of the surface layer of bottom sediments are affected by the burrowing, particle sorting and tube building activities (i.e. bioturbation activities) of benthic fauna such as crustaceans, bivalves and polychaetes. Benthic invertebrates, bacteria and diatoms produce mucus that binds sediment particles together (Madsen et al., 1993; Meadows et al., 1990; Rhoads, 1974).

These activities alter the texture, surface roughness, density, water content and shear strength of bed sediments, particularly muds (Rhoads and Boyer, 1982). Many deposit feeders ingest sediment particles at some depth and eject waste particles at the sediment surface. This waste material may consist of fine particles that are easily resuspended by currents or compacted fecal pellets that behave in a similar way to sand grains.

The remains of dead organisms can also affect sediment properties. In some areas bivalves are very abundant, and their accumulated shells form a dense layer that armours the sediment against erosive forces (Rhoads and Boyer, 1982).

5.8. Surface Pollutant Movement

The previous discussion on advective and dispersive transport and flushing processes that can take place in estuaries applies to dissolved substances, such as salinity and dissolved pollutants, as well as sediments. The behaviour of floating pollutants, such as oil, however, is quite different.

Oil has a very low surface tension, hence its usefulness as a lubricant. This, coupled with its hydrophobic (water-repelling) nature, means that it tends to spread over the waters surface as an unbroken thin film. Oil, when floating on a water surface, undergoes three types of transport:

- spreading
- surface-current advection
- wind-driven advection.

As oil spreads out and is transported across the surface of an estuary, the more volatile fractions evaporate and the more water-soluble fractions dissolve or emulsify with the water mass. Breaking waves facilitate emulsification. In addition to spreading out over the water surface, the oil film is carried along (advected) by surface water currents associated with freshwater and tidal discharges. Variation in surface velocities will result in additional spreading of an oil slick by lateral and longitudinal dispersion.

Finally, wind effects are of major significance to the spreading and transport of floating oil. Table A.4 shows the spread of about 500 litres of oil under a wind speed of 6–9 m/s. After three hours the spread covered 35 ha, whereas under calm conditions it was estimated that the slick would have covered only 2 ha.

The transport of some pollutants can occur in the upper surface layers of the water column (the top millimetre or so) or via surface slicks (compressed micro-layers). Organochlorines and heavy metals have been recorded in micro-layers at concentrations of up to 10,000 times greater than that which would normally occur in the water column (Hardy et al., 1990; Szekielda et al., 1972). Such concentrations may have adverse effects on planktonic organisms that gather at the sea surface. Assessing the extent, concentrations and possible impacts of micro-layers is both difficult and expensive, but their role in estuarine pollution is receiving increasing attention.

5.9. Estuarine Food Webs and Habitats

The tidal, sheltered waters of estuaries support unique communities of plants and animals that are adapted for life at the margin of the sea. Estuarine environments are

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time (hrs)	extent of slick (ha)
1	2.5
3	35.0
5	78.0
10	265.0

Table A.4. Spread of 500 litres of oil under windy conditions (wind speed 6–9 m/s) (Cormack and Nichols, 1977).

among the most productive anywhere, creating more organic matter each year than comparably sized areas of forest, grassland or agricultural land. The productivity and variety of estuarine habitats foster an abundance and diversity of wildlife. Shore birds, fish, crabs and lobsters, marine mammals, clams and other shellfish, marine worms, sea birds and reptiles are among the animals that make their homes in and around many estuaries. These animals are linked to one another and to an assortment of specialized plants and microscopic organisms through complex food webs and other interactions. For example, shore birds use their long bills to obtain fish, worms, crabs or clams. Within the mud, silt, sand or rock sediments live microscopic bacteria, a lower level of the food web, consuming decaying plants.

Many different habitat types are found in and around estuaries, including shallow open waters, freshwater and salt marshes, sandy beaches, mud and sand flats, rocky shores, oyster reefs, mangrove forests, river deltas, tidal pools, sea-grass and kelp beds, and wooded swamps.

The resident and visiting organisms in estuaries must be able to tolerate frequent and rapid changes in salinity, currents, temperatures and water levels. At high tide, seawater changes estuaries, submerging the plants and flooding creeks, marshes, mudflats or mangroves. The incoming waters seemingly bring back to life organisms that have sought shelter from their temporary exposure to the non-aquatic environment. As the tides ebb, organisms return to their protective sediments and adjust to changing temperatures.

Food webs include primary producers and primary, secondary and tertiary feeders, ranging from single-celled algae to the highly efficient predators at the top of the chain. Ecologists refer to these increments as trophic levels. The term trophic means, simply, 'pertaining to food'. The ways in which food is consumed – that is, the pattern of consumption and how it changes with time – is called trophic dynamics.

Inasmuch as an estuary is an environment characterized by rapid and frequent change, which leads to biological diversity, food webs and trophic dynamics in an estuary are complex. Unlike the open ocean, where phytoplankton species are usually the sole primary producers, estuarine systems usually contain several types of primary producers. In addition to phytoplankton, these include sea-grasses and salt-marsh plants. Zooplankton graze on phytoplankton. These, in turn, become food for plankton-eating fishes, such as herring, smelt, and the larvae and young of larger fishes. These, then, become food for carnivores and omnivores nearer the top of the food web.

Some animals graze on the larger estuarine plants, but such plants are probably more important food sources after they die and begin to decompose. Here, bacteria and fungi promote the breakdown of the dead plant material. This organic detritus is an essential source of nutrition for detritus-eating animals and supports a detrital food web.

Benthic, or bottom-dwelling, and bottom-oriented organisms are other important components in estuarine food webs. Clams, for example, reside in the bottom sediments and feed on plankton and other organic matter which they filter from the water. Oysters and mussels are other filter feeders.

Bottom deposit feeders, such as the various kinds of worms found in the estuary, move over and through bottom sediments where they find food deposited in or on the sediments. Shrimps, crabs and other invertebrates are well adapted to bottom feeding, as are many of the estuarine fishes, such as sculpin, flounder, sole and sturgeon. In fact, most fish species that reside in estuaries or move into them on feeding forays are bottom oriented in their feeding patterns.

Near the top of the estuarine food web are various carnivores and omnivores. Some show marked food preferences, while others are opportunistic feeders. These may include diving birds, wading birds, waterfowl, gulls, terns, pelicans, ospreys, trout, perch, striped bass, sharks and salmon. At the top of the food web can be seals, sea lions, whales, larger sharks and humans.

5.9.1. Habitat Zones

Figure A.37 illustrates various ecosystem habitats associated with an estuary. Shown on the figure are nine different habitats.

Fish habitats are mainly underwater. Although not readily visible, they play an important role in an estuary and in the economy of the region. There are many different types of habitats on which fish depend for their survival, ranging from deep ocean water to the shallower areas near the coast to rivers and lakes far inland. Like one

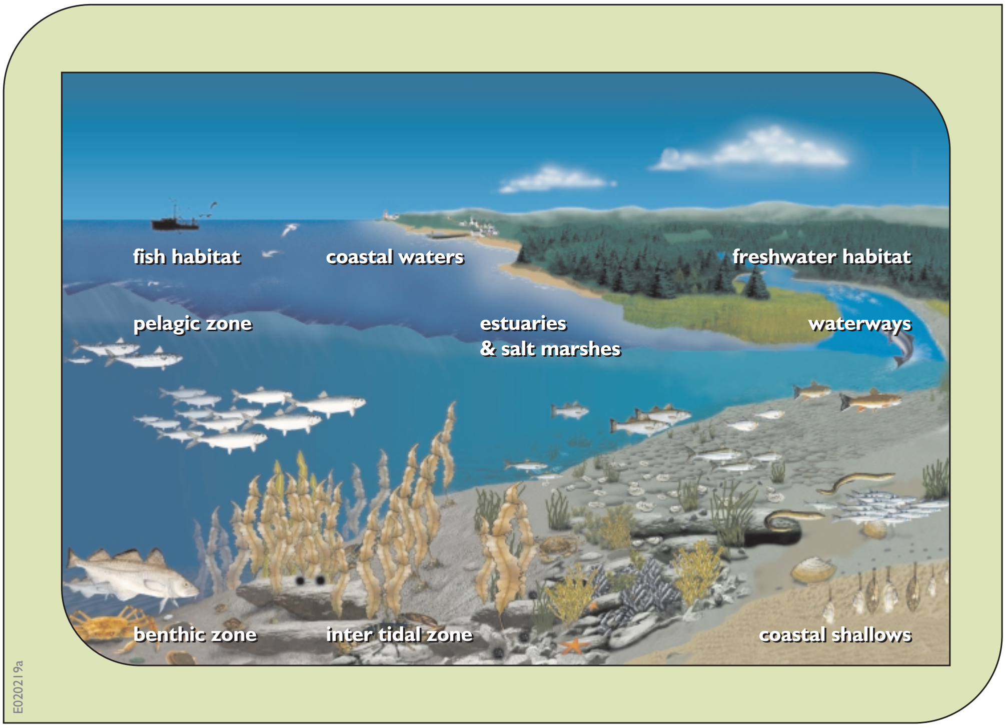

Figure A.37. Typical habitats of an estuary and its surroundings.

giant mosaic, habitat pieces are linked together and support one another. Habitat connectivity is critical. What affects one habitat will in turn eventually affect other, connected habitats.

Coastal waters can support commercial and recreational fishing industries. They can also support a variety of aquaculture activities such as shellfish culture or fish farms. In many communities, fishing is an important contributor to the regular diet of the local population.

Freshwater habitats are not much different from their marine counterparts in supporting a wide and diverse fish population. Lakes provide deep and stable habitats of rocky, sandy and muddy bottoms. Aquatic plants provide food, shelter and spawning areas, as they do in the oceans and estuaries. Unpolluted rivers and streams can offer a habitat of clean, well-oxygenated water. Insects living and falling in the water are a major food source for fish. Fish use the rivers to travel between spawning, rearing and feeding habitats.

Pelagic fish such as mackerel, tuna and herring that live their entire lives just below the surface of the ocean often follow the ocean currents, which are like rivers in the ocean. The fish habitat in these areas can change rapidly due to the actions of the wind, rain, sun and air temperature. The fish follow these 'rivers in the ocean' to areas that are suitable for them to reproduce and feed. They lay their eggs in the open sea or shallow coastal waters. When the eggs hatch, the young drift with the ocean currents. Typically, out of millions that hatch from eggs, only a few survive to become adults.

Many nutrients brought down from streams and rivers pass through estuaries and salt marshes before reaching the oceans. These are among the most fertile areas found anywhere for plants and animals. Coasts that contain extensive estuaries and salt marshes support the fisheries on which many depend. The nutrients fertilize large expanses of the plants along shores. These are the main feeding, growing and sheltering areas for young fish and shellfish. After hatching in freshwater, young smelt drift downstream to the estuaries where they hide and feed among aquatic plants.

Cod, halibut and other fish that live on or near the bottom of the ocean are called 'benthic fish' or 'groundfish'. Others that are harvested from these deep-water areas can include snow crabs and scallops. In the waters nearer to the shore, the fish habitat is a mixture of rock and mud. This near shore mixture can be the home to lobsters, rock crabs, shellfish and smaller fish. The physical and chemical conditions in these areas typically do not change very quickly. If any sudden changes do happen, the effects on the fish habitat and the fish themselves can be severe.

Shallow water habitats are usually a mixture of mud, rocks and gravel. Animals like oysters, clams and mussels that filter the water for food can find abundant food in this habitat. They feed on microscopic animals and plants called 'plankton'. They spend their lives in one place, so their habitat is extremely important for shelter and feeding. Urban or commercial developments along coasts, poorly designed wastewater treatment systems, sewage outfalls and infilling of marshes and bays can all degrade the ecosystem habitat in these areas. The filter-feeding animals in these areas are very sensitive to changes in their habitats such as a lack of oxygen, increases in temperatures or being buried by mud.

In the shallower waters and rocky shores, the increased temperature, sunlight and wave action results in more types of habitats that support more kinds of plants and animals. Plants become very important in this area, transferring the sun's energy through plant-eating animals. This inshore area supports a wide variety of animals that use the plants for food, refuge, hunting grounds and reproduction. For example, periwinkles, urchins and starfish scrape the algae off the rocks and plants, and also lay their eggs on them. These eggs are sources of food for crabs, lobsters and other fish.

5.10. Estuarine Services

Besides serving as important habitats for wildlife, estuaries and the wetlands that often fringe them perform other valuable services. Water draining from the uplands carries sediments, nutrients and other pollutants. As the water flows through fresh and salt marshes, much of the sediment and pollution is filtered out, creating cleaner and clearer water that benefits both people and marine life. Wetland plants and soils also form a natural buffer zone between the land and ocean, absorbing floodwaters and dissipating storm surges. This helps protect upland organisms as well as valuable real estate from storm and flood damage. Salt marsh grasses and other estuarine plants also help prevent erosion and stabilize the shoreline.

Among the cultural benefits that estuaries offer are recreation, a source of scientific knowledge, education and aesthetic aspects. Boating, fishing, swimming, surfing and bird watching are just a few of the recreational activities people enjoy there. Estuaries are often the cultural centres of coastal communities, serving as the focal points for local commerce, recreation and culture. They also provide aesthetic enjoyment for the people who live, work or holiday in and around them.

Finally, estuaries provide tangible and direct economic benefits. Tourism, fisheries and other commercial activities thrive on the wealth of natural resources estuaries supply. The protected coastal waters of estuaries also support important public infrastructure, serving as harbours and ports vital for shipping, transportation, and industry.

To maintain and enhance these and other services and benefits derived from estuaries, they must be managed. This often includes protection and restoration.

5.11. Estuary Protection

The economy of many coastal areas is based primarily on the natural beauty and bounty of estuaries. When those natural resources are imperilled, so too are the economies and well-being of people who live and work there. In many countries that have coastlines, most of their populations are concentrated along them. Populations in coastal regions are growing faster than in inland regions throughout most of the world.

Population pressures and the impact of human encroachment on estuaries, as shown in Figure A.38, is evident. In North America, for example, some 70% of the original sea-grass meadows and salt marshes have been lost in Puget Sound, Galveston Bay and Narragansett Bay. Over 90% of original wetlands have been lost in San Francisco Bay, Chesapeake Bay, Hudson-Raritan Estuary, and Tampa Bay (USEPA, 2001).

This increasing concentration of people living along coastlines tends to change the natural balance of estuarine ecosystems and threatens their integrity. Channels are dredged, marshes and tidal flats are filled, waters are polluted, and shorelines are reconstructed to accommodate human housing, transport and recreational needs. Stresses caused by overuse of resources and unchecked land use practices in some areas have resulted in unsafe drinking water, closing of beaches and shellfish beds, harmful algal blooms, unproductive fisheries, loss of habitat, death of fish and wildlife, and a host of other human health and natural resource problems.

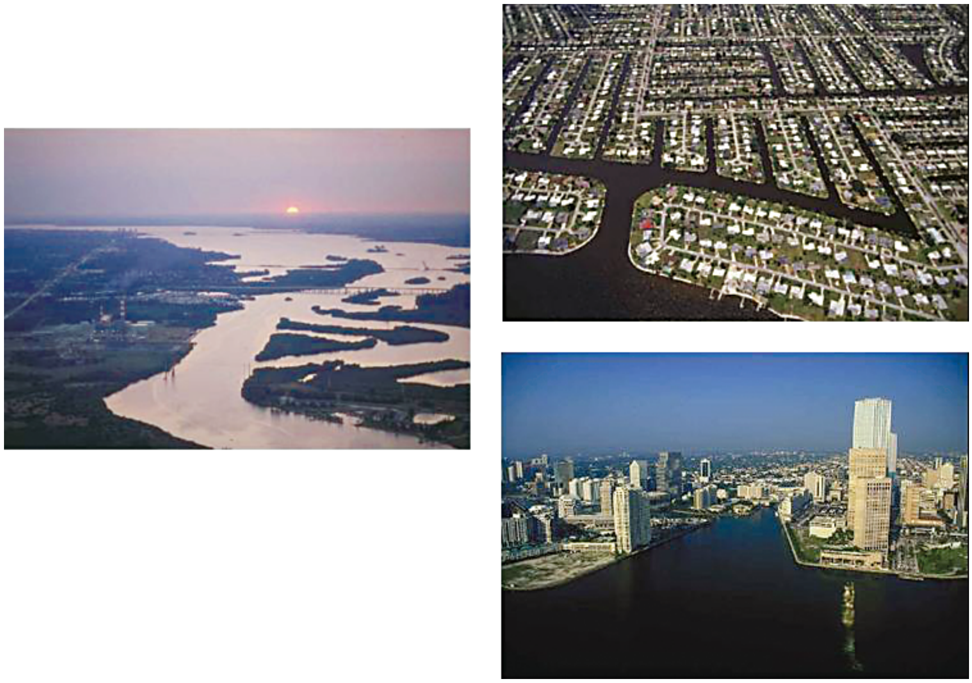

Figure A.38. Not all estuaries remain natural. Some show the impacts of development and the desire for humans to live near and on them. (South Florida Water Management District, West Palm Beach, Florida.)

Polluted runoff from rural, suburban and urban areas upstream of estuaries can also cause damage. Stormwater can pick up contaminants from roads, vehicles, lawns and construction sites, and discharge them into streams, lakes and wetlands. Everything that happens on land in the watershed that drains into the estuary can affect its habitat. When stream channel habitat is degraded, say from agriculture, construction or forestry activities, fish die because their nesting and feeding areas are destroyed. In urban harbours, in particular, polluted runoff creates 'hot spots' of toxic contamination where relatively few species can live. For example, polluted runoff from agricultural chemicals is responsible for the 'dead zone' off the coasts of Texas and Louisiana, which extends some 11,000 km^2 into the Gulf of Mexico. Airborne pollution that falls on estuaries also contributes to their contamination.

Dams blocking river flows can restrict the upstream and downstream passage of migrating fish, isolating them from spawning and feeding areas. The construction of dams accounts for significant and ongoing loss of habitat in the watersheds of many of the world's rivers and estuaries. Without healthy streams, estuaries cannot receive their normal allocation of nutrients. The result is usually reduced productivity. If fewer fish return to the estuary, many living organisms in the food web that depend on healthy fish populations will suffer.

Excessive discharges of pollutants in wastewater effluent from city and industrial sewage treatment plants can degrade estuary ecosystems that require clean water to survive and thrive. This is evident in many if not most of Western Europe's major estuaries; examples include the Tyne, Tees, Humber, and Thames Estuaries in the UK; the Scheldt Estuary in Belgium and the Netherlands; the Ems Estuary in Germany and the Netherlands; the Weser and Elbe Estuaries in Germany; and the Seine Estuary in France. Wastewater treatment can help restore some of the damage done by excessive pollution. When the treatment plants discharging into Tampa Bay (Florida) were upgraded to advanced technology, the sea-grasses – 85% of which had been destroyed – began to grow back, and along with them the fish and other creatures that depend on those grasses. Estuaries can be restored, but it takes time as well as money.

Shifts in climate and the altering of stream channels by humans cause an annual loss of tens of thousands of hectares of estuary habitat. This is of concern along the Louisiana coast of the United States. Changing the course of the Mississippi River as it enters the Gulf of Mexico along the coast of Louisiana has substantially reduced the yearly input of sediment to its delta. The result has been an open-sea encroachment of both the estuaries and dry land. Louisiana estuaries lose about 12,000 hectares of land each year to erosion and subsidence (actual sinking of the land into the water). Delta erosion and loss has also been a problem in the River Nile Estuary since the building of the High Aswan Dam reduced the sediment loads normally carried by the Nile River to the Mediterranean Sea.

Estuarine habitat and freshwater loss is a major challenge to estuarine management throughout the developed and developing world. Population growth and economic development will almost certainly lead to additional loss of habitat and freshwater diversion in many estuaries. The same social driving factors, combined with a continuing migration of human populations to coastal urban centres, require major expansions of engineering infrastructure. Nutrient emissions from human activities can greatly exceed even those naturally carried by large rivers. An increasing number of coastal areas are already manifesting serious effects of nutrient over-enrichment, including bottom-water hypoxia or anoxia, undesirable algal blooms, and the loss of sea-grasses and coral reefs.

5.12. Estuarine Restoration

The most cost-effective route to saving estuaries is to prevent habitat alteration and destruction in the first place. But because of the substantial loss of vital estuarine habitat, and the habitat that continues to be destroyed, restoration is often necessary.

'Restoration' means returning an area of estuary habitat to a successful, self-sustaining ecosystem with both clean water and healthy habitats that support fish and wildlife and human uses of the estuary, such as swimming, boating and recreational and commercial fishing and port activities. Ecological restoration does not usually focus on a single species but strives to replicate the original natural system. The goal is to help rebuild a healthy, functioning system that works as it did before it was polluted or destroyed. Restoration also means an actual increase in the quantity of high-quality estuary habitats, as measured both by their surface area and by their ability to support a resilient healthy ecosystem.

Restoration activities in estuaries range from the simple to the complex. They may include, singly or in combination:

- baseline assessments
- setting performance standards and defining long-term monitoring and conservation plans
- restoring the physical and hydrological conditions through engineered activities, often involving heavy equipment and the returning of tidal waters
- reducing inflows of nutrients, BOD and other pollutants
- chemical cleanup of toxic substances
- revegetation of an area through native plantings or natural regrowth.

Restoration of an estuary is most effectively done by communities that live in the watersheds that impact that estuary. These communities should take a watershed approach to estuary restoration. Estuaries are often at the heart of local economies and traditions. Although they may need additional financial and technical assistance from federal, state and local governments, the people who live near estuaries are the ones who will determine just how successful any restoration effort will be.

5.13. Estuarine Management

To achieve estuarine protection and restoration and all the benefits that can be derived from them, estuaries must be managed. Management must begin with some attention to the impacts of daily activities of people who live in watersheds that drain into the estuaries. These activities can affect the ecological habitat of waterways and estuaries. Everything that enters into a stream or river or any other type of waterway that drains into an ocean will eventually find its way to the estuaries and oceans, and thus can eventually affect the estuarine environment. Pollution or even mud runoff in the water can affect aquatic habitats downstream and interfere with plant and animal reproduction. For example, contaminants washing downstream can cause the closure of shellfish beds for human consumption or kill large numbers of fish.

Although each estuary is unique, many face similar environmental problems and challenges that include urban and commercial development, over-enrichment of nutrients, pathogen contamination, toxic chemicals, alteration of freshwater inflow, loss of habitat, declines in fish and other wildlife, and introduction of invasive species.

The following discussion provides a brief overview of the most common problems facing estuary management and restoration. These problems are primarily caused by human activities.

5.13.1. Engineering Infrastructure

Many engineering developments such as harbours, training walls, navigation channels, reclamation and dredging typically take place in the mouths of estuaries. By virtue of their ability to alter depths significantly in the most tidally sensitive reach, such developments can affect tidal behaviour along the entire estuary. Often complex hydrodynamic-ecological models are needed to estimate the impacts of such infrastructure.

5.13.2. Nutrient Overloading

Nutrients such as nitrogen and phosphorus are necessary for the growth of plants and animals, and to support a healthy aquatic ecosystem. In excess, however, these nutrients can contribute to fish disease, red or brown tide, algae blooms and low levels of dissolved oxygen. The condition where dissolved oxygen is less than 2 mg/l is referred to as hypoxia. Many species are likely to die below that level. The concentration of dissolved oxygen in healthy waters is at least 5 or 6 mg/l.

Nutrients can come from both point sources and non-point sources such as sewage treatment plant discharges, stormwater runoff from lawns and agricultural lands, faulty or leaking septic systems, sediment in runoff, animal wastes, atmospheric deposition originating from power plants or vehicles, and groundwater discharges. Excessive nutrients stimulate the growth of algae. As the algae die they decay, and this decreases the dissolved oxygen in water. Algae also reduce sunlight penetration in the water. Fish and shellfish deprived of oxygen, and underwater sea-grasses deprived of light, will die. Animals that depend on sea-grasses for food or shelter leave the area or die. In addition, the excessive algal growth may result in brown and red tides that have been linked to fish kills, manatee deaths and negative impacts on scallops. Decaying algae may also cause foul smells and decreased aesthetic value.

5.13.3. Pathogens

Pathogens such as viruses, bacteria and parasites, as well as certain types of algae, can be toxic and may cause diseases. When found in marine waters they can pose a health threat to swimmers, surfers, divers and seafood consumers. Fish and filter-feeding organisms such as shellfish concentrate pathogens in their tissues, and people eating them may become ill. Pathogen contamination can result in the closure of shellfishing areas and bathing beaches.

Sources of pathogens include urban and agricultural runoff, boat and marina waste, faulty or leaky septic systems, sewage treatment plant discharges, combined sewer overflows, recreational vehicles or campers, illegal sewer connections, and waste from pets or wildlife.

5.13.4. Toxic Chemicals

Toxic substances such as metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), heavy metals, and pesticides are a concern in the estuarine environment. These substances can enter waterways through stormdrains; discharges from industry and sewage treatment plants; runoff from lawns, streets and farmlands; and deposition from the atmosphere. Many toxic contaminants are also found in sediments and are resuspended into water by dredging and boating activities. Bottom-dwelling organisms are exposed to these chemicals and if consumed may pose a risk to human health. As a result there may be fishery and shellfish bed closures, and bans on the consumption of certain foods.

5.13.5. Habitat Loss and Degradation

The continued health and biodiversity of marine and estuarine systems depends on the maintenance of high-quality habitats. The same areas that often attract human development also provide essential food, cover, migratory corridors and breeding/nursery areas for a broad array of coastal and marine organisms. In addition, these habitats perform important functions such as enhancement of water quality and flood protection, and water storage.

Estuarine ecosystems can be degraded through loss of habitat – such as the conversion of a sea-grass bed to an island of dredged material – or through a change or degradation in structure, function or composition. Threats to habitat include commercial and residential development, highway construction, marinas, dyking, dredging, damming and filling. Wetland loss and degradation caused by dredging and filling reduces the amount of habitat available to support healthy populations of wildlife and marine organisms. All of these activities may result in an increase in the runoff of sediments, nutrients and chemicals.

5.13.6. Introduced Species

Intentional or accidental introduction of invasive species can often result in unexpected ecological, economic and social damages. Through predation and competition, introduced species have contributed to the eradication of some native populations and substantially reduced others, fundamentally altering the food web. Overpopulation of some introduced herbivores has resulted in overgrazing of estuarine vegetation and the resultant degradation and loss of marsh. Other impacts can include:

- alteration of water tables
- modification of nutrient cycles or soil fertility
- increased erosion
- interference with navigation, agricultural irrigation, sport and commercial fishing, recreational boating, beach use
- possible introduction of pathogens.

Sources of introduced species include ship ballast, mariculture and aquarium trade.

5.13.7. Alteration of Natural Flow Regimes

Alteration of the natural flow regimes of tributaries can have significant effects upon water quality and the distribution of living organisms within estuaries. Freshwater is an increasingly limited resource in many areas. Human management of this resource has altered the timing and volume of inflow to some estuaries. Too much or too little freshwater can adversely affect fish spawning, shellfish survival, bird nesting, seed propagation, and other seasonal activities of fish and wildlife. In addition to changing salinity levels, inflow provides nutrients and sediments that are important for overall productivity of the estuary.

5.13.8. Declines in Fish and Wildlife Populations

The distribution and abundance of estuarine fish and wildlife depend on factors such as light, turbidity, nutrient availability, temperature, salinity and food availability. Natural and human-induced events that disturb or change environmental conditions affect the distribution and abundance of estuarine species. Declines in fish and wildlife populations have resulted from fragmentation and loss of habitats and ecosystems, pollution and decreased water quality, over-exploitation of resources, and the introduction of exotic or nuisance species.

Habitat loss and degradation can lead to decreases in the stocks of sport and commercial fish and shellfish, changes in the populations of fur-bearing and waterfowl species, and decreasing habitat for migratory birds and other species. Pollutants such as herbicides, pesticides and other wastes pose a threat to living resources by contaminating the food chain and eliminating food sources. Runoff from farms and cities, and toxic releases, can alter aquatic habitat, harm animal health, reduce reproductive potential, and render many fish unsuitable for human consumption.

Other threats to wildlife include oil spills, bioaccumulation of toxins, outbreaks of contagious and infectious diseases, and algal blooms such as red and brown tides. Over-exploitation occurs when fisherman, trappers, hunters or collectors take so many individuals of a species that its ability to maintain stable population levels is impaired. Introduced species compete with native species for food and habitat. Other causes of decline in fish and wildlife populations include agricultural and logging activities, trawling, boat disturbances, entanglement from marine debris, and changes in freshwater inflow.

6. Coasts

Many factors threaten the resilience of naturally dynamic and generally fragile coastal systems. Most originate from land development and urbanization, pollution, overuse and accelerated sea level rise. The challenge in coastal zone management is to maintain the natural physical variability and ecosystem diversity present in, and all the resulting benefits derived from, coastal systems, while simultaneously satisfying multiple stakeholder interests and competing resource uses and values that often favour the stabilization of such zones.

6.1. Coastal Zone Features and Processes

The coast is where land and ocean interact. It is a zone extending inland to the limit of tidal or sea spray influence. The relative levels of the sea and land determine coast locations. In relation to the land, sea levels fall and rise as glaciers grow and melt over periods of thousands of years. When sea levels rise, as is being observed today, the coasts move inland unless prevented from doing so by barriers. Most efforts to 'protect' the coasts are oriented toward preventing this inland movement and destruction of property – property that is often very desirable and hence very valuable. But coastal beaches are naturally dynamic, adjusting themselves, through erosion and deposition, to the variable and often random forces they are subjected to. Coasts are shaped by land and marine processes, which in turn are increasingly being influenced by human activities and structures that tend to constrain these natural dynamic processes. Preventing erosion, for example, will eventually destroy the beaches, and beaches provide much more than just recreational benefits, as will be discussed below.

Land processes have primarily shaped the irregular, glacially scoured, rocky coasts typically found in higher latitudes. These are characterized by long narrow embayments carved into bedrock. Other coasts have a combined marine and land origin, or a primarily marine one. The Outer Banks of North Carolina on the US Atlantic coastline are barrier islands formed by the rising sea. The Pamlico and Albemarle Sounds behind them, on the other hand, are simply a series of flooded river valleys. The Mississippi Delta comprises sediment that is transported by the Mississippi River into the Gulf of Mexico, where it is sculpted by waves into long fingers of land protruding into the sea. The same is true of the Nile River Delta in Egypt.

Coasts formed by marine processes include much of the US Pacific Coast, with its cliffs formed by wave erosion. Outer Cape Cod, jutting into the Atlantic Ocean in Massachusetts, is another coast formed by the wave erosion of a deposit of glacial sands and gravel. A predominantly marine-formed coast in North America extends from Long Island, New York, to Mexico's Yucatan, with only a few interruptions. These barrier islands just offshore of the eastern coast of the United States occupy more shoreline distance than any other open-ocean shoreline type. The islands are formed by the waves, the wind and the offshore currents.

6.1.1. Water Waves

Every coastal project such as beach nourishment or harbour design requires information on the wave conditions in the region of interest. Increasing demands for accurate design wave conditions and for input data for the investigation of sediment transport and surf-zone circulation have resulted in improved wave-prediction models during the last two decades. Liu and Losada (2002), Dean and Dalrymple (1984), Dingemans (1997), Mei and Liu (1993), Horikawa (1978), Ippen (1966), Kinsman (1965), and Sarpkaya and Isaacson (1981) discuss various theoretical wave models and cite original papers.

In spite of model improvements, the prediction of waves and their effects is still relatively primitive in comparison with the complexity of the real system. Numerical models are still based on simplified governing equations, boundary conditions and numerical schemes, imposing different restrictions to practical applications. The computational effort required to solve a truly three-dimensional wave propagation problem, involving numerous physical processes resulting in hundreds or more wavelengths with different temporal and spatial scales, is still too large to be feasible in engineering design practice at this time.

Local currents, accelerations and pressure fluctuations often accompany water waves. Their simplest form is sinusoidal (Figure A.39).

Small amplitude wave theory is based on the sinusoidal wave shown in Figure. A.39. A right-hand coordinate system is commonly used, with its origin at still-water level. Still-water level, *SWL*, is the water surface that would exist in the absence of any wave action. The x-axis is horizontal and parallel to the direction of wave propagation and no variation is assumed in the y direction, perpendicular to the x-axis.

The sinusoidal water surface level, η, at any time t at location x may be described by:

$$\eta = a\cos\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \tag{A.2}$$

where a is the amplitude of the wave, x is distance in the direction of wave propagation, t is time, L is the wavelength, π(pi) radians is 180° and T is the wave period.

The maximum vertical distance between crest and trough of the wave is the wave height, H (=$2a$). The distance over which the wave pattern repeats itself is the wavelength, L. The waves propagate with a velocity, C, and the time required for a wave to pass a particular location is the wave period T ($T = L/C$). The inverse of the wave period is the wave frequency f ($f = 1/T$). The

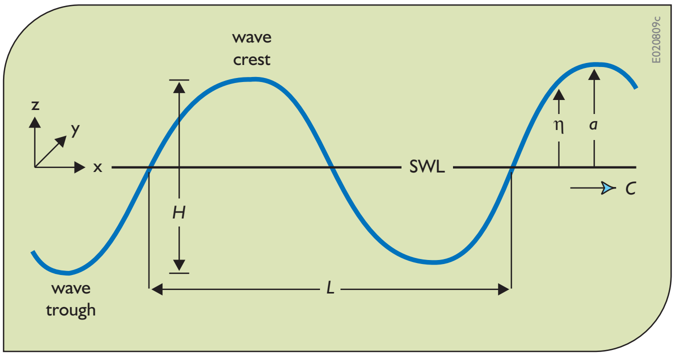

Figure A.39. Basic wave components and characteristics include wave height, *H*, length, *L*, amplitude, *a*, relative to still-water level, *SWL*, and velocity *C*.

ratio of wave height to wavelength (H/L) is called wave steepness.

The high water levels are the wave crests; the low levels are the wave troughs. The crest of waves is measured in the y direction. Swell is normally characterized by long crested waves, each extending in the y direction over a hundred metres or so. Sea normally has short-crested waves with local peaks.

Finally, waves are said to be in deep water when the depth of the water per unit wavelength, L, is greater than 0.5 and in shallow water when it is less than 0.05. Between these conditions, the water depth is called transitional.

Water waves range from capillary waves that have very short wave periods (order 0.1 second) to tides, tsunamis (earthquake generated waves) and seiches (basin oscillations), where the wave periods are expressed in minutes or hours. Waves also vary in height, from a few millimetres for capillary waves to tens of metres for the long waves. Gravity or wind-generated waves are in the middle of that range. They have periods from 1 to 30 seconds and wave heights that are seldom greater than 10 m and mostly of the order of 1 m. They are generated by wind against the gravitational force attempting to restore the still-water level. These gravity or wind-generated waves account for most of the total available wave energy.

The actual shape of a water surface subjected to wind does not look like Figure A. 39. It is a complex combination of many waves of many different wave heights and periods. These waves propagate more or less in the wind direction. Local peaks in the water levels occur when and where the two waves combine, and lower water levels occur when and where the waves separate, resulting in the irregular wave pattern at any particular time and location. Even when the first puffs of wind touch a flat water surface, the resulting distortions present non-linearities that make rigorous analysis extremely difficult, if not impossible. When the first ripples generated by these puffs are subsequently strengthened by the wind and interact with each other, the result is known as a confused sea. As the wind speed and duration increase, the complexity of the waves will increase. Coastal zone modellers need to understand this confusion.

Wind waves generated by a storm over the sea or ocean usually consist of a wide range of wave frequencies. Wave components with higher wave frequencies propagate at slower speeds than do those with lower ones. As they propagate towards the coast, long waves lead the wave group and are followed by short waves. In deep water, wind-generated waves are not affected by the bathymetry. Upon entering shallow waters, however, they are either refracted by bathymetry or current, or diffracted around abrupt bathymetric features such as submerged ridges or canyons. A part of wave energy is reflected back to the deep sea. Continuing their shoreward propagation, waves lose some of their energy through dissipation near the bottom. Nevertheless, each wave profile becomes steeper with increasing wave amplitude and decreasing wavelength.

In very shallow water the front face of a wave moves at a slower speed than the wave crest, causing the overturning motion (the 'breaking') of the crest. Such an overturning motion usually creates a jet of water, which falls near the base of the wave and generates a large splash. Turbulence associated with breaking waves is responsible not only for the energy dissipation but also for the sediment movement in the surf zone.

On large bodies of water, waves can travel well beyond the area in which they are generated. For example, waves generated by a storm off the coast of Newfoundland in Canada may travel easterly toward Europe, eventually arriving with much less energy on the coast of Portugal. Wave energy frequencies are reduced. The resulting waves arriving in Portugal, for example, will be more orderly than the initial sea generated off Newfoundland, with longer wave periods (10–20 seconds), smaller wave heights and more pronounced wave grouping. Waves generated some distance away are called swell.

6.1.2. Tides and Water Levels

Water levels influence both flooding and wave exposure. Most damage to structures along coastlines occurs when the water levels are high. Rising water levels expose shore structures to larger waves because the water depth determines where waves break and thus where they release most of their energy. The increased forces and overtopping of water may damage coastline structures and areas behind it. Conversely, when the water level drops, the same structures may not be exposed to waves at all.

Similarly, high water levels can cause sandy shores to retreat, even if the shores are backed by substantial dunes. Higher water levels allow larger waves to come closer in to the shore. These waves erode dunes and upper beach and deposit the sand offshore. If the water level rise is temporary, most of this loss will be regained at the next low water. Permanent water level rise, however, will result in permanent loss of sand. Shorelines consisting of bluffs or cliffs of erodible material, such as glacial till or soft rock, are continually eroded by wave action. High water levels, however, will allow larger waves to attack the bluffs directly, increasing the rate of shoreline recession.

6.1.3. Coastal Sediment Transport

Although there are many important aspects of coastal zone management, the most important driver and fundamental criterion in a coastal zone management plan is often the movement of sand and other sediment.

The transport of sediment, moved by waves and wind, may be divided into cross-shore and long-shore components. Sediment movement can result in erosion or accretion: removal or addition of volumes of sand. Erosion normally results in shoreline recession (movement of the shoreline inland). Deposition of sediments on beaches (accretion) causes the shoreline to move out to sea. Most protection schemes do not function well with too much cross-shore sediment movement. In particular, if the main cause of shoreline recession is systematic movement of sand offshore, protection becomes difficult.

6.1.4. Barrier Islands

Barrier islands, as illustrated in Figure A.40, are ribbons of sand formed by rising sea levels on coastal plains with low, flat surfaces extending to the edge of the sea, a large supply of sand, and waves large enough to move the sand about. Barrier island migration towards the mainland occurs as the barrier island rolls over itself like a wheel. The ocean side of the island retreats as storms push sand across the island to form sand overwash fans. Overwash fans often extend into the lagoon behind the island and may cause the island to widen in a landward direction. Simultaneous shoreline retreat of the side of the island open to the ocean results in island migration.

6.1.5. Tidal Deltas and Inlets

Inlets usually form during storms when stormwaters that have been forced into estuaries behind a barrier island rush across the island on their return to the sea, cutting a channel through the island. Figure A.40 illustrates a natural inlet.

Tidal deltas, as illustrated in Figure A.40, are bodies of sand formed at inlets by tidal currents. Flood tidal deltas are formed by sand forced into the lagoon between barrier islands and the mainland by incoming or flood tides. The ebb tidal delta is the body of sand pushed seaward by the outgoing or ebbing tide. Salt marshes or mangroves, where mangroves grow and eventually add to the width of the barrier islands, colonize flood tidal deltas. Overwash fans also add to the width of barrier islands once the inlet migrates or opens to the sea.

When an inlet is jettied to stabilize a navigation channel, the ebb tidal delta is broken up. For a few years or decades after jetty construction, the sand from the ebb tidal delta ends up being deposited on adjacent shorelines. Eventually a new and completely submerged tidal delta forms far offshore at the end of the jetties, taking sand permanently away from the beach.

6.1.6. Beaches

Beaches are strips of unconsolidated material found at the seaward margin of the coast. The location of the beach shoreline, the wet–dry boundary of the beach, moves up and down with the tide. (Maps usually show the mid-tide line or mean sea level.) A beach on a barrier island or spit is called a barrier beach, and beaches between rocky headlands are called pocket beaches.

Beach materials are subjected to wind, waves and currents, which shape the beaches accordingly. They

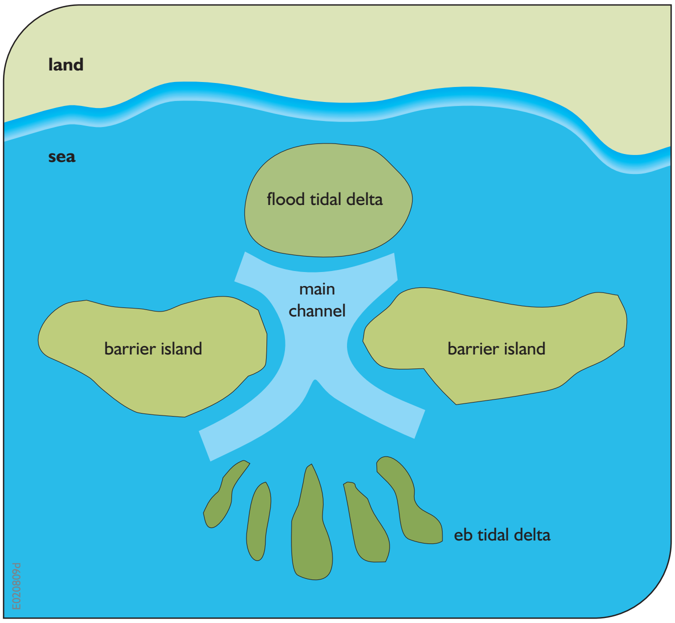

Figure A.40. Barrier island main channel inlets cut through a barrier island and tidal deltas.

constantly adjust to wave and tidal energy, the quality and quantity of the sediment supply, and level of the sea. One of the challenges confronting coastal zone managers is to predict the future behaviour or movements of beaches.

Beaches can be classified by the size of the material on them (e.g. mud, sand, gravel, boulders), or by the type of material (e.g. volcanic, coral, quartz). Beaches can also be referred to as high energy, moderate energy or low energy beaches according to some average regional wave height.

Storms dramatically increase wave energy, which is proportional to wave height, as well as a rise in sea level. Beaches adjust their shapes in response to this higher energy environment. Sand will be moved, offshore bars may form, or the beach may flatten out. The storm-related rise in sea level helps waves reach dunes or bluffs, washing dune sand back to the beach. This addition of sand and sediment on the beach further buffers the waves and wind. The amount of sand movement and the ultimate shape taken by the beach will depend in part on this sediment supply and the grain size of the beach material.

During a storm the beach flattens as sand moves from the upper to the lower beach. This dissipates wave energy over a broadened surface relative to the beach before the storm. After the storm the sand will gradually return to nearly its pre-storm profile.

As shown in Figure A.41, beaches are steeper during calm weather, and flatter during storm events. All beaches with a reasonably good sand supply and no seawall will respond to strong storm waves by either flattening or forming offshore bars. Beaches that flatten in response to large waves cause breaking waves to dissipate their energy over a broader surface. Waves that reach cliffs before having their energy dissipated must dissipate their energy over a relatively short distance. The result of course is a spectacular rise of water into the air. Offshore bars are small ridges of sand parallel to the shore that can also help dissipate the energy of breaking waves. Their presence is evident when incoming waves break one or more times before reaching the shore.

Beaches usually recover after each storm or storm season. The sand that moved offshore under the influence of the larger storm waves moves onshore under the influence of the smaller fair-weather waves. Offshore bars flatten or gradually move onshore, and the beach between the low- and high-tide lines tends to become steeper over time. The onshore distance depends on the size of the storm or severity of the storm season.

Beach grain size also affects the slope of the beach. High-permeability gravel for example absorbs much of the water that falls on it; hence, the return flow energy is much less than the incoming flow energy. In this case the forces pushing beach material up onto the beach are stronger than those moving material seaward in the backwash. The beach becomes steeper in response. On beaches of fine sand, the permeability of the material is much less than for gravel, so relatively little water from breaking waves is absorbed. The backwash of the wave has essentially the same volume of water as the upwash. This backwash volume tends to move sand in a seaward direction thereby flattening the beach.

6.1.7. Dunes

Beaches can be major sources of material for the land as well. Sand blown inland from the beach piles up as sand dunes, sometimes forming large dunes that move further inland. Some of these large dunes can be big enough to cover up trees and roads as the dunes move inland, as occurs on the US Pacific Coast near Florence, Oregon.

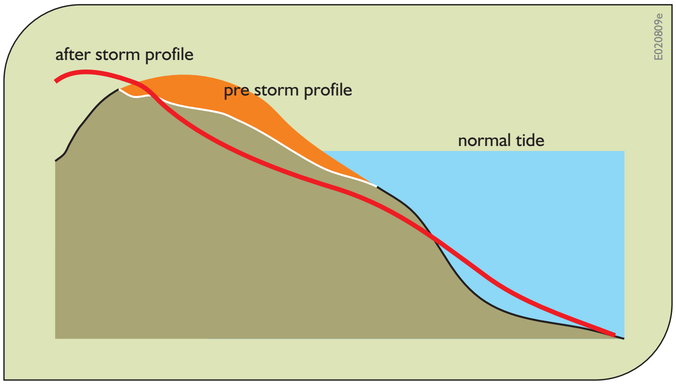

Figure A.41. Possible response of a beach to a major storm. Cross sections show steeper pre-storm profile, a possible shallower after-storm profile (denoted by the dark red line), and the recovering beach profile, showing some loss of its original steepness, sometime after the time of the storm.

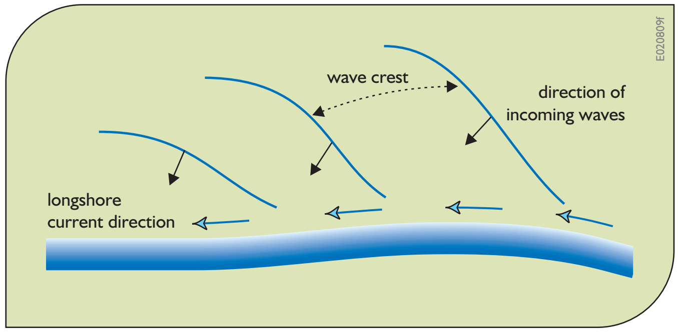

Figure A.42. The energy from breaking waves at the shoreline can cause longshore currents. These currents are responsible for transporting beach sand laterally along the beach.

6.1.8. Longshore Currents

Sand moves because of wind, waves and currents. The largest volume of sand is often carried by longshore currents. Such currents are created as waves strike the shoreline at an oblique angle, forcing some of the surf-zone water to move laterally along the shore, as illustrated in Figure A.42. Breaking waves suspend sand, and the currents move it. Sandy beaches are actually rivers of sand.

Beach material comes from the land as well as the seabed. Rivers supply sediment that eventually reaches the coast and ends up on beaches. Eroding cliffs along the coast are also sources of beach material. For most of the US East Coast, the continental shelf is an important source of sand, which is brought to the shore by the circular motion of the waves. Calcareous marine organisms are often contained in this continental shelf sand. In tropical waters the skeletal material of calcareous marine organisms can make up the entire beach, providing the sparkling white or pink colour characteristic of, for example, some Caribbean beaches.

6.2. Coasts under Stress

Many coastal areas are under pressure from a number of causes, mostly stemming from increasing human populations. Coastal regions tend to have substantially higher population densities than elsewhere. Today about half the US population lives 'near' (within easy driving distance of) the coast. In countries like Australia and Canada a much higher percentage of the population lives along a coast. Most of the world's major cities are located along coasts.

Historically the economy of coastal zones depended on fishing, boating or boat building. Today's populations are engaged in a much greater range of occupations that give them a higher standard of living and quality of life, even in increasingly expensive and crowded coastal regions.

Continued migrations of people to coastal regions for jobs, recreation, more moderate weather and a higher quality of life have increased the stress on coastal zone resources. Resorts along the Mediterranean coast, South Florida and the Caribbean islands, for example, have witnessed large increases in the tourism and recreation industries. Coastal areas along the western border of North America have seen substantial increases in residential development for people desiring the lifestyle associated with the coast.

Coastal zones are relatively scarce commodities. They are just narrow strips of land along a coast. The high demand for this limited real estate invariably results in relatively high land prices and in the costs of using various facilities located along the shore. In addition, many coastal lands are fragile. They erode easily. This puts a high priority on protecting and maintaining what is there.

6.3. Management Issues

Individuals like to live, work and play along coasts. This is evidenced by the continued higher proportion of population growth and economic development along

Figure A.43. Encroaching residential development along a coastal beach and estuary.

the coastal regions of just about every country in the world that has them. Most of the world's mega-cities (populations in excess of 10 million) are coastal. As suggested by Figure A.43, coastal areas provide attractive environments for residential as well as economic development in spite of their occasional natural hazards and changing landforms. Changing land cover and use that accompany population growth in coastal zones affect the geomorphological and ecological processes that take place along coastal shorelines.

Coastal zone management is the management of conflicts among multiple conflicting uses of natural and human resources in highly populated and economically, ecologically and often geopolitically important coastal zones. Coastal zone management focuses on the economic development and use of the environmental and ecological resources of coastal regions in ways that protect, and in some cases restore, them.

Coastal zone management historically focused on providing protection of shoreline properties against floods, and the design and construction of harbours and marinas (that is, the infrastructure associated with commercial and recreational boating). Today, coastal zone management involves much more than protection of land from being eroded by the sea and transportation on the sea. Issues such as water quality, dispersion of pollutants and the proper management of the complete coastal ecosystem have become important. Structural design is now only a small aspect of coastal management.

Current coastal zone management issues include reducing the risk of erosion from coastal storms, protecting bays, sloughs (channels) and sounds where rivers meet the sea, preserving and restoring beaches and ecological habitats, enhancing economic development and recreation opportunities along urban waterfronts, and controlling polluted runoff – the major source of pollution in coastal waters today.

The development of technically, economically and environmentally appropriate management plans requires an understanding of the complexity of coastal zone processes that probably no single person has mastered. It requires an understanding of the effects of the natural variability of wind and waves and temperatures as well as the effects of structural development, over-fishing, excessive pollution, habitat destruction and human population shifts. Inputs are needed from many individuals who have expertise in one or more aspects of coastal zone management and who are willing to work with others who have different expertise and experiences.

This necessary expertise and experience may have to include river basin management as well as coastal zone management. Some coasts are affected by what happens in upstream river basins. If those basins drain into coastal estuaries, it may be important to consider the effects of basin management on the coastal zones. For example, much of the sediment along some of North America's Pacific Ocean coasts is brought to those coasts by rivers that discharge their waters and sediment into the Pacific Ocean. Damming these rivers typically diminishes the sediment load, that is, the sand being transported to the coast. Much of the sediment that would otherwise end up on beaches is trapped behind the dams, even though these dams can be many hundreds of kilometres upstream of the beaches.

Consider, for example, the impact the High Aswan Dam has had on the Nile Delta. The policy of keeping the downstream flows from reaching flood stage has resulted in a shrinking of the delta at the mouth of the river as it discharges into the Mediterranean Sea. Similarly, reduced sediment loads in the Mississippi River, along with sea level rise, have contributed to the reduction of the delta of the Mississippi River on the Gulf Coast of the State of Louisiana.

6.3.1. Beaches or Buildings

For most of the world's beaches, if there were no people there would be no coastal zone management problems. As humans place obstacles such as houses, apartment buildings, highways and seawalls along a beach, the dynamic processes that maintain natural beaches are constrained. Shoreline erosion, and hence its retreat inland, is blocked. The beach jams up against these structural objects. This causes it to narrow, which in turn leads to a reduction in the supply of sand to adjacent beaches.

Since there is a worldwide tendency for all but very rocky coasts to erode, protecting and maintaining them is a high priority, particularly given the high economic value of coastal land. The economics of coastal zone protection and maintenance are complex. But is it seldom economically feasible to invest in shoreline protection unless there is very dense development or extensive tourism. Areas such as Miami Beach in southern Florida in the United States, the Gold Coast in Australia, Scheveningen in the Netherlands, Copacabana in Brazil and the Chicago and Toronto waterfronts on the Great Lakes are prime candidates for coastal protection. Agricultural areas and areas of single-family residential properties, on the other hand, are not. Yet protection decisions are not just based on economics. Decisions about what to protect are often political as well.

Consider, for example, the coastal management strategy of the Netherlands. Much of the Netherlands, being below sea level, depends on coastal protection. One single storm event in 1953 breached the dykes along the coast and drowned nearly 2,000 people. The loss of livestock and property was extensive. The result was a decision to provide protection from sea storms as severe as those expected once in every 10,000 years. This is a storm intensity having a probability of 0.00001 of occurring in any single year.

Alternative strategies for flood protection in the Netherlands include withdrawal from areas where further erosion may occur, selective erosion control, full erosion control, and expansion in the seaward direction by artificial beach nourishment where the coastal defences are considered to be weak. Full erosion control and perhaps expansion in threatened areas would appear to be almost a necessity for this densely populated and flood-vulnerable country. Full control involves placing 6–10 million m^3 of sand along the coast annually.

6.3.2. Groundwater

Freshwater in maritime coastal regions usually comes from two sources: rivers and lakes, and groundwater aquifers. When precipitation is sufficient to keep the groundwater levels higher than the surrounding sea level, the higher density saltwater does not mix with the freshwater. A floating freshwater lens will lie on top of the denser saltwater.

If withdrawals of freshwater from groundwater aquifers along coastal regions lower the freshwater level to below the seawater level, a flow of saltwater from the sea into the groundwater aquifer can occur. Since the flow rates of groundwater are very small, there is little mixing of the salt and fresh groundwater. The freshwater reservoirs of small island communities are therefore very susceptible to saltwater intrusion if population pressures along the coasts cause over-pumping of the aquifer for freshwater supplies. Similar damage can be caused by cutting away the dunes and thus lowering the water table, by increasing the amount of impervious surfaces that increases runoff and reduces aquifer recharge, and by dredging of rivers that can increase saltwater intrusion upstream.

6.3.3. Sea Level Rise

A potentially significant change in sea level may come from changes in the global climate. Global warming since the last glaciation has resulted in a sea level rise of 100 to 150 metres through melting of the polar ice caps and thermal expansion of the water in the ocean. This process continues at a rate estimated to be about 1 to 1.5 mm/yr. Any additional warming would increase this rate.

Global climate change models estimate the water level rise resulting from increases in greenhouse gases and hence increases in temperature, glacier ice melt and ocean thermal expansion. Such numerical models have produced a range of scenarios, and these predictions of water level increases are by no means precise. There are many uncertainties in the estimates of production of greenhouse gases. Probably the most uncertain is the extent to which gas emissions will be controlled, a matter that is unpredictable and largely political. The methods used to translate these uncertain atmospheric pollution figures first into global warming and then into water level rise also involve many assumptions that are uncertain. Nevertheless, the impacts of sea level rise are fairly clear:

- More severe storms (tornadoes and hurricanes) will occur more often.
- While storm surge will decrease a little because of the larger water depths, it will also increase because of the more severe storm activity.
- Offshore, the waves will be higher, because of more severe storms.
- Tides appear not to be significantly affected.
- Tidal prisms will increase, because the surface area of the bays and estuaries will increase.
- Waves breaking on shores and structures will be higher because larger depths all the way into shore will reduce bottom friction losses, as well as permitting large breaking waves to come closer into shore.

The result:

- Structures will be subjected to higher stress from the higher waves; factors of safety will decrease.
- Structure runup and overtopping will increase, adding to the risk of flooding and damage by overtopping. As an example, the Delta Project in the Netherlands raised all dykes in response to the 1953 storm surge, yet a 1-m sea level rise would reduce the present margin of safety by about 90% (Wind, 1987).
- Sandy shorelines will retreat.
- Barrier islands will roll back more rapidly and marshes behind the barrier islands will disappear.
- Deltas will not build out at the same rate; they may even retreat.
- Bluffs and cliffs will retreat more rapidly.
- Sediment transport rates will increase, possibly filling currently stable inlets and harbour entrance channels.
- Saltwater intrusion into groundwater tables will increase.
- Many wetland areas will be inundated and disappear.

How can everyone prepare? Flood protection, shore protection and navigation structures can be strengthened and raised to cope with the rise in water level. If all else fails, a properly executed retreat can be planned in which buildings are moved back from the shore or abandoned.

The magnitude of the problem can be huge. Population densities along the ocean shore are already high and rapidly increasing. Sustainable development of the coastal areas in the face of rising sea levels will be an important issue and challenge in this century. Moreover, although flood defences such as dykes can be raised with presently available technology, the risk to people and properties behind those dykes increases.

The main casualties will be the already limited wetland areas. Their development can keep up with slowly rising sea levels and move inland, but they may have problems adjusting to a more rapid rise in water levels. Also, since most of the properties behind the wetlands are usually dedicated to human activities and uses, it is unlikely that wetlands will be allowed to intrude into this valuable real estate. Damage will also occur to agricultural areas because of the additional saltwater intrusion.

Sustainable shoreline development through maintaining the existing shorelines by retro-fitting, retreat by moving infrastructure inland, and meeting the concerns for wetlands and agriculture, will require a complete restructuring of most current political and policy-making processes. They typically are not designed to deal with slowly developing impacts over very large areas.

6.3.4. Subsidence

Although subsidence can occur naturally, it is often caused by human activities, for example, pumping groundwater, petroleum and natural gas out of the ground. Subsidence of coastal landmass results in increased flooding. It exacerbates the effects of rising sea levels, since the relative sea level rise with respect to the land will be even greater. One of the best known examples of subsidence coupled with a rising sea level can be seen in the city of Venice, where increased pumping of both water and natural gas has caused an accelerated rate of subsidence. The result is more frequent flooding of an increasingly large portion of the city. As a result, the city and its mediaeval monuments are subjected more and more regularly to 'aqua alta' or high water.

6.3.5. Wastewater

Coastal waters have traditionally been used for wastewater disposal. Increased discharges of sewage and chemical effluents, particularly since the Second World War, have polluted many coastal waters. Although large oceans and lakes are often thought to have almost unlimited dilution capacity for wastewater, they do not. In many cases those dilution limits have already been reached, and many are showing serious overload and eutrophication problems. Even though some offending chemical dump sites have been cleaned up, the toxic chemical content of organisms in the aquatic ecosystem, including the fish for example, can remain at high levels for considerable times after cleanups are completed.

Cleanup of any coastal area is a complex undertaking, but even more so if it requires altering the pollutant discharge actions of many nations. There is still the prevailing philosophy of 'out of sight, out of mind', when it comes to the discharge of pollutants into maritime coastal waters.

Many maritime communities still discharge raw sewage, often into the near-shore zone. Even communities that have adequate sewage treatment prior to discharge often discharge sewage into coastal waters during heavy rainstorms due to combined sewer overflows (CSOs). With heavy rainfall, the combined sewage and stormdrain flows can exceed the hydraulic and treatment capacities of the sewage treatment plant, and the excess water (overflow) containing some raw sewage is discharged directly without treatment.

Beach pollution is less likely if the sewage outfall is piped and diffused into the coastal waters many kilometres offshore, as occurs at Sydney, Australia. Many outfalls are mere open channels that discharge storm and wastewaters relatively close to shore. The discharged pollutants, trapped by currents and wave action, can flow right along the coastline, leading to unacceptably high pollutant concentrations near the shore.

People have discharged raw sewage into the sea because it has been a relatively cheap way to dispose of it. If beach closures and the accompanying economic losses happen often enough, the added costs of wastewater treatment and disposal methods might be a less costly alternative. Tertiary wastewater treatment costs about ten times as much as dumping raw sewage. Incineration, if acceptable, costs even more.

Two recent examples of actions taken to clean up coastal zones, at considerable cost, have been those for reducing the discharge of pollutants into the estuary adjacent to the city of Boston on the northeastern Atlantic Coast of the United States (Figure A.44), and into the Tagus Estuary adjacent to the city of Lisbon in Portugal.

6.3.6. Other Pollutants

Runoff from farming can also be harmful to coastal waters, particularly bays and lagoons. Runoff that contains fertilizers used to promote the growth of agricultural products also promotes the growth of algae and aquatic weeds. Pesticides contain high levels of toxic substances, such as heavy metals. Even without the chemicals, runoff from farmlands can be undesirable. The manure from the high-density populations of cattle and pigs causes high levels of nitrates in both the groundwater and the surface waters. The runoff of fine sediment materials from soil erosion resulting from the conversion of forests to agricultural land has also caused problems for many maritime organisms. The death of coral reefs in many tropical countries can be attributed, at least in part, to the sediment that has entered the water column since the land was cleared for agriculture, as early as the eighteenth century in some cases.

Oil spills resulting from transportation and exploration of oil close to shore, such as the spill from the Exxon Valdez in 1989 (Figure A.45), have been the cause of well-known and costly disasters. The *Prestige* oil spill off the northwest coast of Spain in November 2002 involved twice as much oil as the *Exxon Valdez* spill. Areas along major shipping routes are particularly vulnerable, as witnessed by the spills of the *Torrey Canyon* in 1967, the *Amoco Cadiz* in 1978 and the *Erika* in 1999, all along the northwestern coast of France. Although such major incidents cause some government action, much larger volumes of oil are routinely released with virtually no restrictions each year into the oceans from ships and petroleum production platforms and refineries.

Figure A.44. Deer Island Sewage Treatment Plant in Boston Harbour treats and discharges an average daily flow of about 380 million gallons (1.43 million m^3) of wastewater. (With permission of Piping Resources Partnership of New England.)

Hazardous solid waste is another major source of pollution of coastal waters. Although ocean dumping legislation severely limits the dumping of solid waste in many countries, the oceans continue to be the recipient of all sorts of solid hazardous wastes, including hospital waste, contaminated dredge spoil and nuclear material.

6.3.7. Mining of Beach Materials

Mining of sand and other beach materials is one of the major causes of beach erosion in some beaches. Sand mining for construction and other uses occurs on many scales, but the accumulated impact can be substantial along some coasts.

6.4. Management Measures

Coastal zone management is the management of the land and its uses along the coast. Thus it is the management of conflicts. It requires legislation and enforcement of measures to protect and enhance the sustainable use of lands along shorelines. Coastal zone managers need scientific, technical and political skills, skills based on an understanding of geology and morphology, biology, ecology, law, planning and engineering among other disciplines. Although coastal zone management is interdisciplinary, it is usually the engineers who are asked to make and implement crucial technical decisions. To do this well, they need to be properly informed, and work with specialists from many other disciplines.

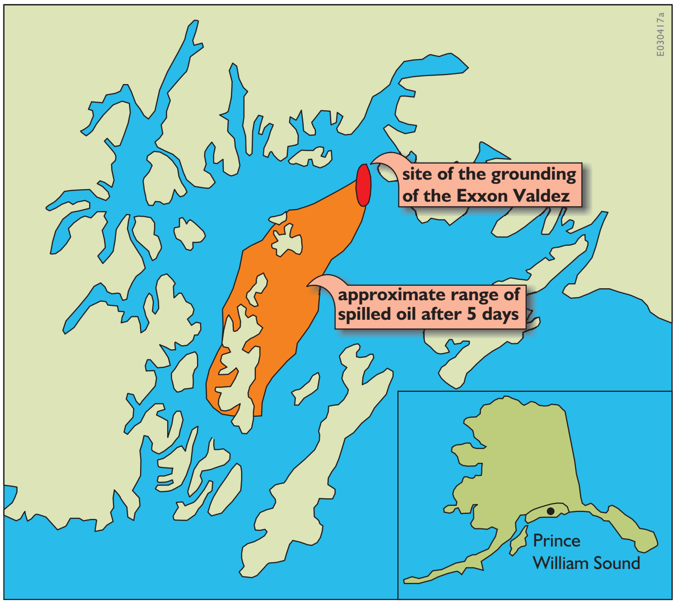

Figure A.45. Site of Exxon Valdez oil spill in the US State of Alaska, 1989.

Management options include structural as well as non-structural measures such as zoning, regulation enforcement, public awareness activities, negotiation and consultation. These tools need to be part of an appropriate adaptive decision-making process.

6.4.1. 'Conforming Use'

Coastal zones have traditionally supported many activities, all of which compete for limited space and may or may not conflict with each other. Some of the more important uses of coastal lands include tourism, residential, recreational, industrial and commercial activities, agriculture, transportation, waste disposal, aquaculture, fishing, nature reserves, and military and security functions. (Not all of these may be present along any given coast.)

Given the high demand for limited space along a coast, one approach to coastal zone resource management is to limit development to only those 'conforming uses' that need to be along the coast. Examples could include swimming beaches, fishing ports and marinas. Amusement parks, casinos, theatres and car parking areas that are often found along a coast can be located more inland from the beach. Development (building) permits for beach property could be limited to those projects that need to be there.

Implementing a restrictive zoning policy is not simple. For instance, developments that attract people to an area, such as harbours or marinas, are normally required by law to supply sufficient infrastructure to support their operation. Does a car park suddenly become a conforming use, if it is needed in support of a conforming use? Similarly, money generators such as casinos are usually permitted to locate along the coast regardless of conforming use. The installation of adequate public transportation from inland casinos, hotels and parking lots to coastal shorelines could alleviate some of this political as well as economic pressure for non-conforming uses right along shorelines.

In many coastal regions, abandoned older facilities are being taken over by interests catering to tourism. Facilities such as factories, ports and railway lines are being converted to more conforming uses. Warehouses and loading terminals are being transformed into apartment buildings, abandoned railway lines are serving as biking and hiking trails, and small commercial ports are becoming marinas and condominiums. These transformations are taking advantage of unique opportunities, but they also present unique challenges.

In environmentally sensitive regions, tourism can be a positive influence. Proper coastal management is, in part, aimed at enhancing the intrinsic value of the area for tourism. The definition of intrinsic value of the coast is also changing. Highways, parking lots, hotels and fast-food restaurants are typical features of many tourist areas, but an increasing number of tourists demand other aspects, especially along coastlines. They seek bicycle paths, dunes, wetlands, clean water, birds and fish. Increasing numbers of tourists are more interested in nature and prefer physical activities such as hiking, biking, birding, boating and fishing to simply sitting on the beach soaking up the sun and a few six-packs. The coastal environment they want is much more natural than the traditional amusement park type of environment dominated by concrete and French fries. (Obviously, many tourists like both the concrete and the sun and sand.)

Whatever tourists seek, tourism development is clearly motivated by economics. Enhanced recreational (as well as environmental and ecosystem) planning must be done within an economic framework that sustains the continued coastal zone development, maintenance, protection and restoration activities.

6.4.2. Structures

Many types of structures are built along coastlines to meet the needs of people who visit or live there. The focus here is only on those that are built to protect property from damage by waves and currents along the coasts.

There are three available responses to local shoreline erosion problems:

- hard stabilization, such as seawalls (Figure A.46), offshore breakwaters (Figure A.47) and groynes (Figure A.48)
- soft stabilization, such as beach sand replenishment
- relocation of threatened structures.

Each response has its advantages and disadvantages. Hard stabilization alternatives involve armouring the shoreline with structures designed to hold it in place. This may be the best way to save buildings, but not beaches. Removing buildings or relocating them further inland is the best way to save beaches, but obviously not the buildings in their current locations. Hard stabilization combined with beach replenishment may provide necessary protection for both buildings and beaches, but it will be necessary to continually add sand to the beach over time.

6.4.3. Artificial Beach Nourishment

Artificial nourishment is an alternative to structural measures for protection. It has the least impact on adjacent properties and the environment. Instead of harming the surroundings, a beach fill can benefit adjacent eroding properties. Apart from its cost, the diffusion and advection of a beach fill only presents a problem when water depth needs to be maintained at the adjacent properties, such as in navigation channels, or when the sand added to the system threatens valuable habitat.

Although this approach has been used for many years, the technology is still very much intuitive. Artificial beach nourishment is subject to the same erosion that caused the need for replenishment in the first place. The design of such programmes must therefore be concerned not only with how much sand to place, but also with how often it needs to be replenished. Artificial nourishment in most areas then becomes a beach maintenance programme based on annual cost–benefit estimates. If the site erodes more rapidly as a result of offshore conditions, such as a locally steeper shoreline or a convergence of wave energy, the artificially placed fill will also be subjected to the same conditions and will not perform well.

Since a major objective of most artificial nourishment schemes is to provide protection as well as additional recreational beach space, most schemes consider beach fills in combination with shore face nourishment. Beach fill normally requires rehandling of the sand so that it can be placed by pipeline dredge and perhaps be reshaped by earthmoving equipment. The onshore sand is usually placed with a steep seaward slope. The wave action on such a fill will shape the most seaward part of the fill mass into a beach profile. During this adjustment period – and at any later time, when other beach material further landward is redistributed – fine grain sizes will be winnowed out of the mass of sand and lost to deep water, until the grain size distribution of the remaining sand mass is similar to the native distribution. Once the fill has been

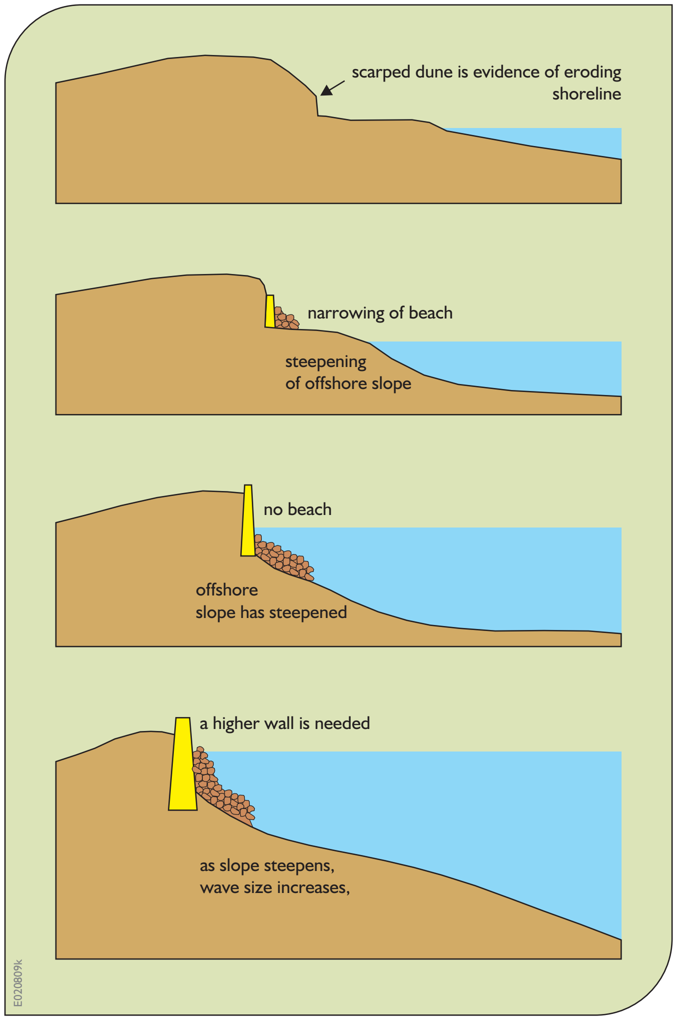

Figure A.46. Seawalls designed to protect property. Larger and stronger seawalls are needed over time as the beach disappears in front of them.

re-adjusted by the waves to form a beach profile, a steep scarp may have formed at the top of the beach.

The combination of artificial nourishment with structures such as groynes or offshore breakwaters will help contain the fill material. Structures also provide an opportunity to use beach fills in areas that would never be stable with artificial nourishment alone. Examples are Hilton Head on the US Atlantic Coast (Bodge et al., 1993) and Norderney on Europe's North Sea Coast (Kunz, 1993).

Biologically, a beach is relatively unproductive. Benthic communities that are covered by a beach fill seem to re-establish relatively quickly after nourishment. The surrounding ecosystem, however, can be affected and thus

Figure A.47. Eastern Scheldt Storm Surge Barrier along the North Sea coast of the Netherlands, a seawall eight kilometres long. Its sixty-two openings are closed off with sliding barriers at high tide.

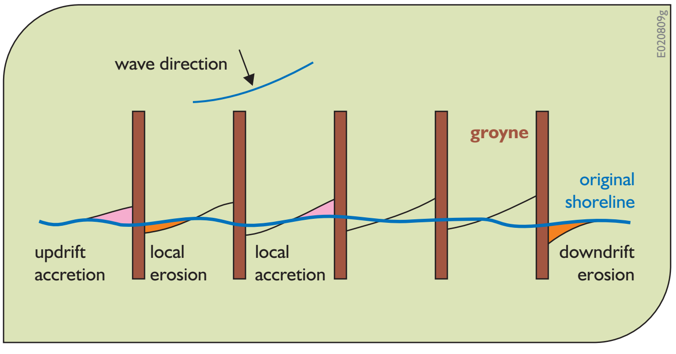

Figure A.48. Groynes are often used to reduce shoreline erosion. They change the longshore sediment transport rates and result in accretion updrift of the groynes within the groyne field and downdrift erosion.

should be carefully considered and monitored (CUR, 1997; NRC, 1995; Simm, 1996).

7. Conclusion

This concludes an overview of the many components, functions and processes that take place in watersheds and river basins, wetlands, estuaries and along coasts, and the ways in which these processes can be affected by land and water management policies and practices. This appendix provides an introductory background for those who have not had separate courses in these subjects and who are now being introduced, through this book, to the art of building and solving water resources planning and management models. The purpose of these models is to predict how, and to what extent, these system components, functions and processes are affected by alternative ways of managing and using these land and water resources.

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