VI.8

Provisioning Services: A Focus on Fresh Water

Margaret A. Palmer and David C. Richardson

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Healthy freshwater ecosystems play crucial roles in the global environment by controlling fluxes of minerals, nutrients, and energy, and, by providing goods and services critical to humans including water for drinking or irrigation and fish for consumption. Freshwater ecosystems also provide regulating services such as carbon sequestration, flood control, and cultural services such as recreational fishing, swimming, or aesthetic enjoyment of the open water. These goods and services are all supported by underlying ecological processes (also called ecosystem functions) such as primary production, decomposition, and nutrient processing. The well-known and dramatic decline in freshwater biodiversity that has occurred in the last several decades has been accompanied by local and regional losses of freshwater ecosystem services. These losses are being driven largely by human activities. Ecosystem services cannot be restored once lost without a focus on the underlying ecological processes that support them, and, thus, a great deal of research is ongoing to understand and quantify the linkage between services and the rates of key ecological processes.

GLOSSARY

anaerobic. Absence of oxygen, also called anoxic (e.g., anaerobic sediments).

chemotroph. An organism that makes its own food but, instead of using energy from the sun as photosynthetic organisms do, uses inorganic chemicals as an energy source; includes wetland bacteria called methanogens that produce methane (a greenhouse gas) by decomposing organic matter in anaerobic environments.

denitrification. The microbial process that converts nitrate (NO_3^-, nutrient readily available to plants) to nitrite to free nitrogen gas (N_2, generally unavailable to plants); requires a carbon source and an anaerobic environment.

geomorphology. The study of the formation, alteration, and configuration of landforms and their relationship with underlying structures.

hydrology. The study of the properties, distribution, and effects of water on the earth's surface.

hyporheic zone. The subsurface region under and lateral to a stream in which groundwater and surface water mix; considered metabolically important in streams and rivers.

organic matter, particulate and dissolved. Derived from the degradation of dead organisms, plant or animal; particulate organic matter would include leaf pieces, wood, animal body parts, etc.; dissolved organic matter refers to organic molecules that are typically less than 0.7 μm; also called dissolved organic carbon.

point- / non-point-source pollution. Point-source pollution comes from clearly identifiable local sources, includes outlet pipes from wastewater treatment plants or other industrial sources. Non-point-source pollution comes from many diffuse sources and is carried by rainfall or snowmelt as it moves over or through the ground to fresh water. These pollutants include excess fertilizers, herbicides from agricultural or residential areas, oils or other toxic chemicals from urban runoff, salt from roads or irrigation practices, bacteria or nutrients from livestock, pet waste, or pollutants from atmospheric deposition.

primary and secondary production. The production of new living material through photosynthesis by autotrophs (e.g., plants, algae) is primary production; tissue produced by heterotrophs (e.g., macrofauna, fish) is referred to as secondary production because these organisms rely on the consumption of living or dead organic material.

recharge/discharge. Movement from surface water belowground into an aquifer "recharges" the aquifer, whereas movement from the groundwater back to surface water represents discharge from an aquifer.

1. INTRODUCTION

Only about 3% of the world's water is fresh water, and most of that is bound up in glaciers, underground aquifers, or ice pack. Yet the entire human population depends on fresh water for drinking and on the goods and services provided by freshwater ecosystems. In fact, since antiquity, humans have chosen to live and work near water bodies, and entire civilizations have developed along waterways. Today, most people rely on rivers and streams for their domestic water needs as well as for irrigation, energy, and recreation. They rely on wetlands and riparian buffers to purify water, mitigate the impacts of flooding, and support diverse assemblages of plants and wildlife. Healthy freshwater ecosystems also play crucial ecological roles globally by controlling fluxes of minerals, nutrients, and energy. Indeed, all ecosystems worldwide depend to some extent on freshwater ecosystems and the complex connections that exist among terrestrial flora and fauna, groundwater, surface waters, and water vapor (plate 20). Biodiversity and ecosystem processes in terrestrial, polar, and coastal ecosystems are all influenced by inputs of fresh water and fluxes of organic matter and other materials from rivers and streams.

As outlined in earlier chapters in this section (chapters VI.1 and VI.2), ecosystem services can be categorized as provisioning, regulating, or cultural. Provisioning services are those "products" obtained from ecosystems such as fish for consumption or water for drinking or irrigation. Regulating services include nonmaterial benefits that humans receive from ecosystems such as water purification, carbon sequestration, or flood control. Cultural services represent nonmaterial benefits as well, such as recreational fishing, swimming, or aesthetic enjoyment of the open water, but we choose to focus on provisioning and regulating services in this chapter. As we describe below, each provisioning and regulating service is supported by underlying ecological processes (figure 1). In some cases, just a few processes may support a service, and in other cases, a whole suite of complex processes interact to provide the basis for a service. For example, water purification may rely on the ecological processes of denitrification, decomposition of organic matter, and algal photosynthesis, whereas riverine flood control may depend almost exclusively on the presence of healthy (intact) floodplains. Species also rely on ecosystem services to provide them with food, optimal conditions for reproduction, and dispersal routes, to name a few.

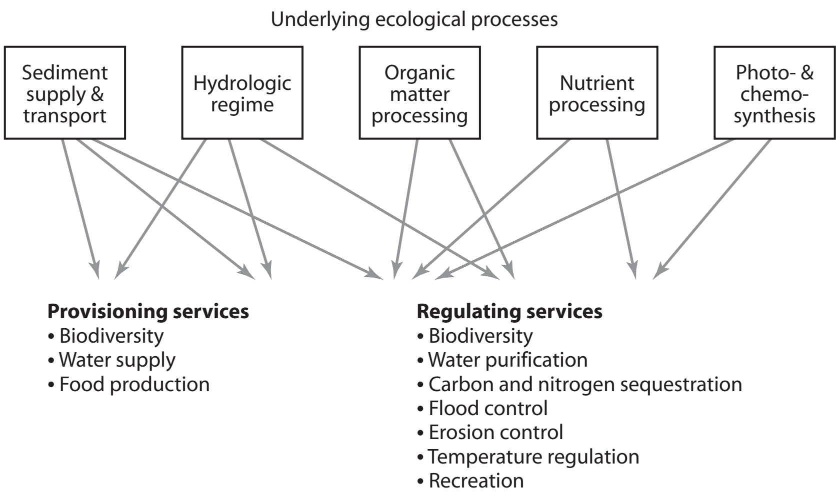

Figure 1. Examples of basic ecological processes that support the services provided by freshwater ecosystems. Subcategories of processes (e.g., denitrification as one component of nutrient processing) are described in table 1. Provisioning services are products obtained from ecosystems, whereas regulating services include nonmaterial benefits.

Because freshwater ecosystems are extremely diverse, as are the services they support, we begin with a brief description of the major types of ecosystems and then move into a detailed discussion of the services they provide.

- *Wetland ecosystems:* Any ecosystem that is regularly, but not necessarily continuously, saturated by precipitation, surface water, or groundwater and is occupied by vegetation that is adapted to saturated conditions; includes bogs, swamps, fens, and tidal or nontidal freshwater marshes.
- *Running-water ecosystems:* Any ecosystem with flowing water that is a low point in the landscape where water drains, especially after rain; perennial streams flow most of the year through well-defined channels; intermittent streams flow only part of the year; and ephemeral streams flow only after major rain events; however, hyporheic flow, which is not readily visible, may persist. Running-water ecosystems include rivers, streams, creeks, and brooks.
- *Lake, pond, and reservoir ecosystems:* Any body of water filling a depression in the landscape that may have been formed in a variety of ways including glacial retreat, tectonic events, river overflows or meanders, and natural damming of running waters (e.g., beaver ponds); their outflow may feed streams and rivers.
- *Glaciers and ice pack ecosystems:* Any body of ice on a mountaintop or in polar regions where snow accumulation exceeds or equals melting; these are slowly moving or have moved at one point in time; once believed to be barren but now known to harbor diverse flora and fauna.

2. FRESHWATER ECOSYSTEM SERVICES AND THE PROCESSES THAT SUPPORT THEM

Healthy fresh waters are living, functional systems. Valuable ecosystem services that they support include water storage and supply, the purification of water through the removal of excessive nutrients, contaminants, and sediments, carbon and nitrogen sequestration, food production in the form of invertebrates and fish, support of biodiversity in aquatic and nearby terrestrial habitats, flood control, and recreation (table 1). Each service is supported by one or more ecological processes (figure 1) that, if lost, could lead to degradation of that service. Societal preferences can lead to choices that enhance one service at the loss or decline of another, and this is often accomplished by influencing the underlying process. For example, if people want abundant trout fisheries in a region, they may stock rivers with hatchery-reared juveniles (effectively enhancing the "fish reproduction/recruitment process"), which may in turn lead to a decline in the productivity of other fish species because of competition for food. Even the act of meeting basic human needs such as providing warmth for people in cold winter months can enhance the provisioning of one service (heat production from burning wood) at the expense of another (carbon sequestration in living trees that provide wood resource).

There is a great deal of active research now to identify ways to measure ecosystem services by quantifying their linkage to the rates of the underlying ecological processes. The motivation to measure ecosystem services comes in part from recognizing that in any coupled social–ecological system, there will always be trade-offs that need to be balanced, with potential needs for compensation if something valuable is lost. Take, for example, extractive mining that can reduce water quality. Communities may find they need to engage in extractive mining as a source of income; they may partially compensate for the degradation in water quality at that site by enhancing water purification at other points in the watershed. A second example might be reforestation around housing developments; the forests lost when houses were built are reestablished to provide opportunities for recreation. No single patch can provide the full suite of services residents might want, but landscape-level management can provide a bundle of services that contribute to human well-being.

The motivation to link the rates of ecological processes to ecosystem services follows directly from the need or desire to enhance or restore a service that has been lost or degraded. Services cannot be restored without a focus on the underlying ecological processes that support them. For example, denitrification, an ecological process that contributes to the ecosystem service of water purification, occurs in many freshwater ecosystems (table 1), but knowledge of the rate of nitrogen removal is necessary to estimate whether denitrification improves water quality. Many surrogate metrics for system performance have been used in assessments of freshwater ecosystems (e.g., plant biomass, sediment carbon content); however, to date, there is no published work in which such surrogates have been directly linked to the *rate* of a specific ecological process and, therefore, to the magnitude of impact on ecosystem service. Thus, an extremely active area of research is now concerned with how to quantify these services, the spatial and temporal variability of these services across and within different biomes, and the potential use of valid surrogates for measuring the underlying process rates that are less

Table 1. Rivers and streams provide a number of goods and services that are critical to their health and provide benefits to society; the major services are outlined along with the ecological processes that support the function, how it is measured, and why it is important.

Ecosystem service	*Consequences of losing the service*	*Supporting ecological process*	*Measurements required*	*Ecosystem/ habitat*
Water purification				
Nutrient processing	Excess nutrients (eutrophication) can build up in the water, making it unsuitable for drinking or supporting life; in particular, algal blooms resulting from excess nutrients can lead to anoxic conditions and death of biota	Retention, storage, and transformation of excess nitrogen and phosphorus; decomposition of organic matter	Direct measures of rates of transformation of nutrients; e.g., denitrification (production of N_2 gas, conversion of NO_3 to more usable N forms); decomposition measured as rate of organic matter loss over time	Riparian zone, river and streambeds, wetlands, lake littoral zones
Processing of contaminants	Toxic contaminants kill biota; excess sediments smother invertebrates, foul the gills of fish, etc.; water not potable	Biological removal by plants and microbes of materials such as excess sediments, heavy metals, contaminants, etc.	Direct measures of contaminant uptake or changes in contaminant flux	Riparian zone and wetland soils and plants; bottom sediments of rivers, lakes, and wetlands
Water supply	Loss of clean water supply for residential, commercial, and urban use, irrigation supply for agriculture	Transport of clean water throughout watersheds	Measures of water movement, flow patterns, pollution load	Lakes, rivers, streams
Flood control	Without the benefits of floodplains, healthy stream corridor, and watershed vegetation, increased flood frequency and flood magnitude	Slowing of water flow from land to freshwater body so flood frequency and magnitude reduced; intact floodplains and riparian vegetation buffer increases in discharge	Measure stream and river discharge responses to rain events	Floodplains, wetlands, riparian zones
Infiltration	Lost groundwater storage for private and public use; vegetation and soil biota suffer; increased flooding in streams	Intact floodplain, riparian, wetland vegetation increase infiltration of rainwater and increase aquifer recharge	Infiltration of water in soils, water table levels in deep and shallow wells	Wetlands, streams, floodplains

Carbon sequestration				
Primary production	Water and atmospheric levels of CO_2 build up, contributing to global warming	Aquatic plants and algae remove CO_2 from the water or atmosphere, convert this into biomass, thereby storing carbon	Measure rate of photosynthesis typically based on loss of CO_2 or production of O_2	Freshwater ecosystems with sunlight but particularly shallow water habitats such as wetlands or midorder streams
Secondary production	Water and atmospheric levels of CO_2 build up, contributing to global warming	Production of biomass by microbes and metazoans stores carbon until their death	Biomass accumulation over time or measures of consumption, decomposition, or chemotrophy	All freshwater ecosystems but particularly the bottom sediments for microbes
Nitrogen sequestration				
Primary production and secondary production	Secondary production supports fish and wildlife	Creation of plant or animal tissue over time	For primary production, measure the rate of photosynthesis in the stream; for secondary, measure growth rate of organisms	All freshwater ecosystems and habitats
Food production				
Primary production	Reduction in food and food products derived from aquatic plants such as algae, rice, watercress, etc. Decreased production (secondary) by those consumers who rely on primary production as a food source	Production of new plant tissue	Measure rate of photosynthesis typically based on loss of CO_2 or production of O_2	All freshwater ecosystems and habitats with sunlight but particularly shallow water habitats such as wetlands
Secondary production	Reduction in fisheries including finfish, crustaceans, shellfish, and other invertebrates	Production of new animal tissue or microbial biomass	Measure biomass changes over time or use measures of fisheries harvest	All freshwater ecosystems and habitats but particularly the water column and surficial sediments
Biodiversity	Loss of aesthetic features, impacts aquarium trade, potential destabilization of food web, loss of keystone species can impact water quality	Diverse freshwater habitats, watersheds in native vegetation, complex ecological communities support multiple trophic levels	Identification of species, functional groups or food webs	All ecosystem and habitat types but particularly wetlands for plants and rivers for fish

(*Continued*)

Table 1. (*cont.*)

Ecosystem service	*Consequences of losing the service*	*Supporting ecological process*	*Measurements required*	*Ecosystem/ habitat*
Temperature regulation	If infiltration or shading is reduced (as a result of clearing of vegetation along stream), stream water heats up beyond what biota are capable of tolerating	Water temperature is "buffered" if there is sufficient soil infiltration in the watershed; shading vegetation keeps the water cool; water has a high heat capacity which stores excess heat	Measure the rate of change in water temperature as air temperature changes or as increases in discharge occur	Shallow water habitats, especially wetlands
Erosion/sediment control	Aquatic habitat burial impacts fisheries, decreases biodiversity, increases contaminant transport; reduction in downstream lake or reservoir storage volume	Intact riparian vegetation and minimization of overland flow	Flood-related sediment movement	Wetlands, streams, and rivers
Recreation/tourism/ cultural, religious, or inspirational values	Lost opportunities for people to relax, spend time with family; economic losses to various industries, particularly tourist-oriented ones	Clean water, particularly water bodies with pleasant natural surroundings such as forests, natural wildlife refuges, or natural wonders	Time spent using resource recreationally; revenue generated from boats, tourist attractions, hotels	Lakes, rivers, streams

time consuming than direct measurements of the process rates themselves.

Most of the ecological processes that support freshwater ecosystem services are themselves influenced by underlying hydrologic and geomorphic processes such as the flux of water and the supply (and transport) of sediment. There is now abundant scientific evidence that hydrologic interactions including groundwater/surface water interactions, the timing of low and high flows (or water cover), and the magnitude of flows in running-water systems or the period of inundation drive many ecological and biogeochemical processes.

3. STATUS OF FRESHWATER ECOSYSTEM SERVICES

Freshwater ecosystems are among the most impacted ecosystems on earth. In most industrialized countries in the world, extensive loss of wetlands and riparian ecosystems has already occurred, and the remaining habitats continue to be under threat. Degradation of lakes and streams is also extremely common worldwide. The U.S. Environmental Protection Agency reported in 2000 that more than one-third of fresh water in the United States is officially listed as impaired or polluted. Worldwide, over half of all wetlands have been altered, and over 1.3 billion people lack access to an adequate supply of safe water.

Major pollutants in freshwater ecosystems include excessive sediment, fertilizers, herbicides, pesticides, harmful pathogens, and industrial by-products such as heavy metals or PCBs. Agriculture is the source of 60% of all pollution in U.S. lakes and rivers, and in Europe, municipal and industrial sources contribute pollutant loads to lakes and rivers. In developing countries, industrialization and population growth will yield increasing pollution loads from both agricultural and industrial sources, but there are few data and little monitoring from those freshwater ecosystems. Excessive nutrients (e.g., nitrogen and phosphorus needed for plant growth) are the leading pollution problem for lakes and the third most important pollution source for rivers in the United States. The nutrient load generates algal blooms, which can spoil drinking water, make recreational areas unpleasant, and contain harmful toxins or pathogens. The eventual decomposition of the algal bloom creates anaerobic conditions in the water that can kill fish and other aquatic organisms. Heavy metals and other industrial by-products can enter the aquatic food web and accumulate in organisms, including those harvested for human consumption. According to the U.S. Environmental Protection Agency, statewide advisories for freshwater fish warn of concentrations of pollutants, namely mercury and PCBs, at levels of human health concern.

Climate change is bringing major challenges in some parts of the world as the freshwater ecosystem services are being impacted by increasing water temperatures, more precipitation in some areas, more droughts in other areas, and in many regions more intense storms. In arid regions, the extraction of surface water and groundwater is so severe that some major rivers no longer flow to the sea year round, and local communities regularly experience water shortages. Today, the Colorado River is often a dry stream at its mouth in Mexico because of damming, irrigation, and use for drinking water in the southwestern United States. The Yellow River, in China, now ends hundreds of miles from its historical mouth because of the diversion of water for irrigation and drinking. People have been forced to move from the watersheds because of periods of drought and flash floods. In wet regions, rivers and wetlands have a natural ability to absorb disturbances such as those associated with floods, but this buffering has been lost in many areas because of the diversion of surface water and development in the watershed. In urban watersheds, removing vegetation and soil and replacing them with impervious surfaces lead to higher peak discharge and greater volume and frequency of floods than in rural or forested streams.

Freshwater ecosystems near developed (urban, suburban, or residential) or agricultural areas have lost many ecosystem services because of runoff from the land, storm drains, sewers, and municipal point sources. Urban areas occupy only a small fraction of the U.S. land base, but the intensity of their impacts on local rivers can match that of agriculture. The impervious parking areas and rooftops that are associated with urban centers, and poorly managed or tiled agricultural fields, have reduced infiltration capacity and lowered aquifer recharge. This, along with channelization of stream networks, has led to lower water tables and lake levels and to more intense flooding in streams. Wetlands and all associated services are often lost entirely because wetlands are being drained and converted to agriculture, residential, or urban lands, lost as a result of road or highway construction, or stripped to harvest construction materials.

Dudgeon and colleagues grouped the major stressors on freshwater ecosystems into five categories (figure 2), and it is now well accepted that the combination of these stressors has led to very high extinction rates for freshwater species. In fact, extinction rates of freshwater fauna are estimated to be at least five times higher than those of terrestrial or avian species. Around the world, we are losing fish, amphibian, and macroinvertebrate species at alarming rates. For example, overfishing, dam construction, water diversion, and pollution have led to the severe decline of commercial and recreational fish

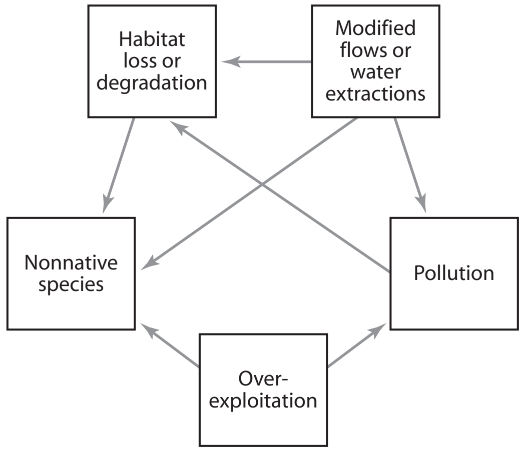

Figure 2. Five major categories of impacts that threaten freshwater biodiversity and ultimately other ecosystem services. (Modified from Dudgeon et al., 2006)

species, such as the American shad in the Hudson and Delaware rivers or Chinese paddlefish in the Yangtze River.

4. THE FUTURE OF FRESHWATER SERVICES

Among the greatest challenges that face many nations worldwide are how to sustain, restore, or judiciously manage the services that freshwater ecosystems provide and how to meet human demand for fresh water. Practices that ensure enough water for drinking and irrigation have received the most attention. In some rapidly developing countries, such as India and China, industrial water demands are beginning to increase, and agricultural and domestic needs from growing populations continue to stress water resources. These problems will be exacerbated in areas that are expected to have less water with global climate change, such as southern Africa, central and northern South America, the Middle East, and parts of China.

Urbanization and climate change, both increasing with population growth, can have negative synergistic effects; freshwater ecosystems, particularly in urban watersheds that receive more precipitation or have more intense storms, will be hard pressed to provide ecosystem services. In areas with snowpack, earlier snowmelt caused by warmer temperatures may lead to massive flooding if the melting coincides with late winter or early spring rains. In these regions, erosion of stream banks and loss of entire wetlands may occur. Lakes may experience greater stress from sediment inputs, and, if they are in urban watersheds, contaminant inputs may also increase following rains. Summer flows to rivers, wetlands, and lakes that are typically sustained by an extended period of snowmelt will be reduced.

The management responses that are needed to protect freshwater ecosystems vary depending on water stress (use-to-availability ratio), land use, how extensively runoff events change relative to current patterns, and needs of people within the watershed. In general, society will have to continue to stress many freshwater ecosystems in order to provide water for irrigation and urban populations, among other things. In fact, some ecosystem services will continue to be lost because a positive benefit is derived from the activities introducing the stress, such as water diversion for human use and crops, infrastructure in the watershed that provides housing or industry, or energy from hydroelectric dams. As indicated earlier, other freshwater systems may need to be preserved or restored to provide water purification, habitat for important aquatic species, or opportunities for recreation. A balance has to be achieved between those services humans receive from converting or stressing freshwater systems and the benefits they receive when those systems are left relatively intact.

Management decisions need to take into account the full range of costs and benefits of provisioning, regulating, and cultural services. Provisioning services, such as fisheries harvest, have a market value and identifiable profits and tend to drive decisions about converting freshwater systems. However, regulating and cultural services are often overlooked because their values are harder to define with no explicit market and diffuse societal benefits. Although a return to pristine, precolonial freshwater ecosystems is clearly unrealistic in the world today, the best management decisions will be made when there is an adequate understanding of all ecosystem services and estimations of their material and nonmaterial values.

When the goal is to restore or protect a freshwater ecosystem, a sensible approach is to take proactive measures to enhance or restore resilience and resistance because this approach may also lead to environmental benefits such as increased water quality and restored fish and plant populations. Palmer and colleagues have outlined examples of such measures including stormwater management in developed basins or, even better, land acquisition around freshwater bodies and riparian corridors to eliminate infrastructure in wetlands and floodplains and allow regrowth of vegetation. If such actions are not taken, we will be left reacting to damages and loss of ecosystem services. Some services may be replaceable by technology (e.g., water purification facilities, levees), but such measures could be extremely expensive and only tenable on fairly small scales.

Protection of freshwater ecosystem services remains a major challenge because it requires preservation, conservation, and management of freshwater ecosystems and their surrounding watersheds. Future research is needed to understand rates and variability of ecosystem processes and how those processes influence ecosystem services. These measurements will allow scientists to make better forecasts about how freshwater ecosystem services will change with global climate change, modifications in land use, and other future stresses. Finally, the scientific research community; public stakeholders; and management at local, state, and national levels must work together to ensure the sustainability of freshwater ecosystem services.

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