Rivers and Global Change

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Abstract

The ecology of streams and rivers varies predictably from headwaters to mouth and regulates the ecosystem goods and services (EGS) of freshwaters and coastal zones of oceans. Headwater streams are particularly important in biogeochemical cycling and nutrient retention, whereas larger rivers are more important for fisheries support and water supply for drinking, irrigating crops, and industry. Increases in population density, urbanization, intensive agricultural, and migration of these activities to higher latitudes with climate change will greatly alter the complex interactions between the ecology of streams and rivers, the EGS they provide, and the human well-being that they support. Projected changes in water temperature, regional rainfall, storm intensity, and droughts with climate change increase threats to water supply and other EGS, which are already major problems today. Solutions to these problems can be initiated with known management strategies and refined with continued research on relationships among human activities, stressors, EGS, and human well-being.

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Definition

Climate and land use change will alter the ecology of streams and rivers, the ecosystem goods and services they provide, and the human well-being they support if management strategies are not initiated to control stressors from global change.

Ecosystem Goods and Services of Streams and Rivers

Human activities reduce the ecosystem goods and services (EGS) provided by streams and rivers, with great variation related to global patterns in climate, climate change, geology, hydrology, culture, and economy (Bates et al. 2008). Streams and rivers provide water for drinking, irrigation, and industrial processes, fisheries, recreation, navigation, hydroelectric power, and support for biodiversity. Human alterations of temperature and weather by climate change as well as pollution and physical changes in watersheds will complexly affect EGS as a result of positive and negative interactive affects among these stressors, nonlinearities, feedbacks, and differing responses of EGS along gradients of human disturbance. The complexities of global change ecology are compounded by the great variation in linkages between ecological and social systems and natural differences among streams, rivers, and biogeoclimatic regions in which they occur (Smith et al. 2009; Stevenson 2011). Changes in rivers and streams resulting from global change were predicted more than a decade ago (Carpenter et al. 1992), and today, we have evidence that many of those predictions have started to occur.

Streams and rivers are key routes for transportation and transformation of matter and energy across landscapes ranging from continents to small islands. Although streams and rivers contain a small proportion of all water on the planet ($\approx$0.0002 %), most water, particularly freshwater, travels through streams and rivers on its way to lakes and coastal zones of oceans. The ecology of streams and rivers varies greatly and predictably from headwaters to mouths where rivers empty into the coastal zones of lakes and oceans. This predictable pattern has been called the river continuum (Fig. 32.1, Vannote et al. 1980) and holds for EGS as well as basic ecology of rivers and streams. Headwater streams are narrow channels that gradually widen as water accumulates within river basins and erodes a wider and wider channel. Most of the biological activity in streams is associated with the bottom, because they are shallow. When streams are very narrow and in biomes with forests, a tree canopy covers the stream to shade the bottom and restrain growth of algae on the stream bottom. But riparian trees deposit leaves into the stream to nourish the ecosystem. The leaves are shredded by aquatic insect larvae

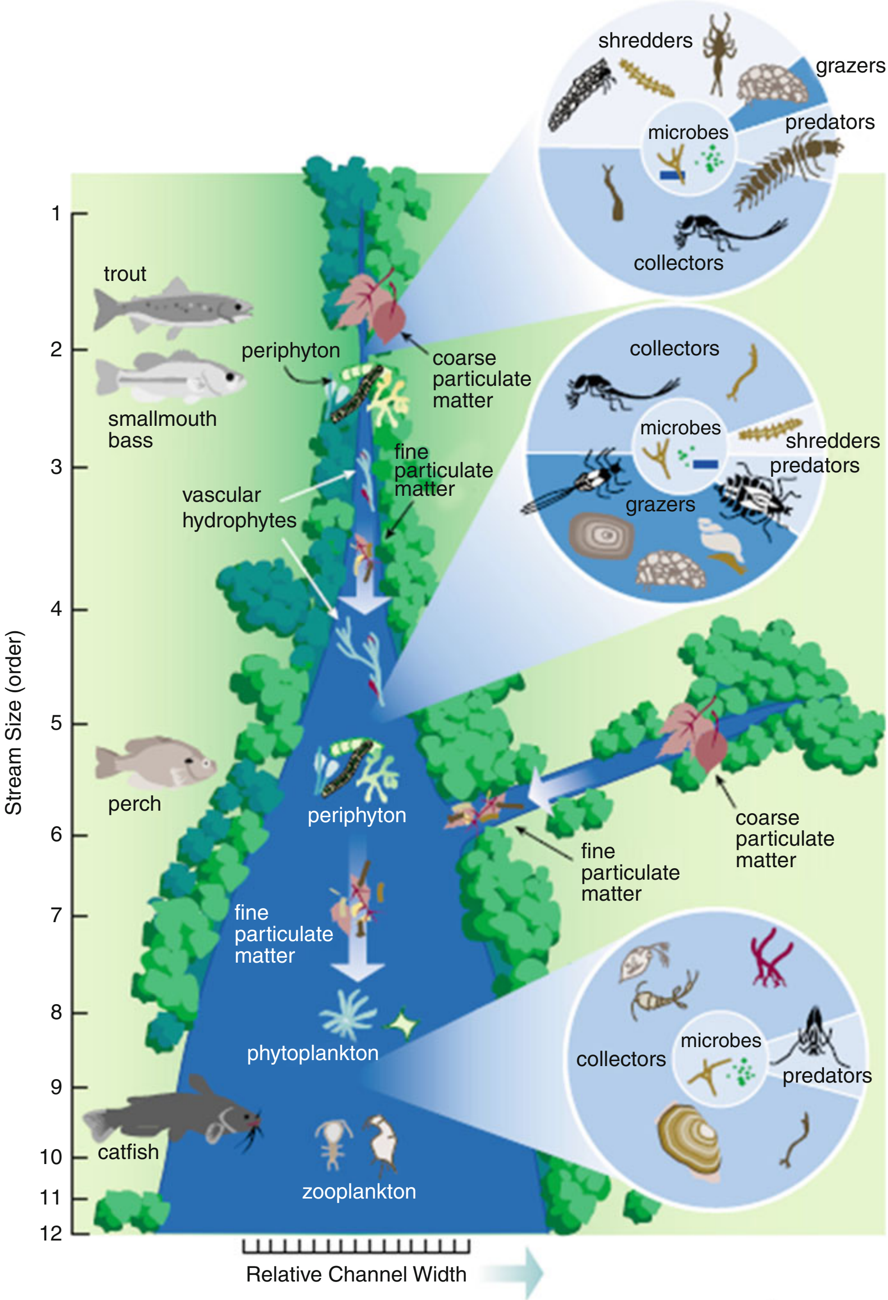

Fig. 32.1 Illustration of the river continuum concept from Vannote et al. (1980) © 2008 Canadian Science Publishing or its licensors (Reproduced with permission and redrawn in FISRWG (1998))

into smaller and smaller pieces which become small enough that they easily float downstream. This fine particulate organic matter is filtered from the water by aquatic insect larvae using fan-shaped appendages or nets spun with secretions. Other aquatic insect larvae swim across deposits of fine sediments and consume them with appendages modified to collect particles from the stream bottom. Bacteria and fungi (decomposers) coat this coarse and fine particulate organic material, decompose the more labile parts, and also harvest organic molecules and inorganic nutrients that are dissolved in the water to further nourish the aquatic insect larvae that were either shredding, filtering, or collecting the organic matter that originated outside the stream channel.

In wider streams, when the tree canopy cannot shade the bottom, or narrower streams in deserts, grasslands, or alpine biomes without trees, algae grow prolifically across the stream bottom. These "benthic" algae absorb inorganic nutrients from the water and photosynthesize to enable their prolific growth. Benthic algae are consumed by grazing insect larvae and snails, nourish bacteria and fungi, and then drift downstream to be captured by the filter-feeding aquatic insect larvae or collected from the bottom after settling in slow current areas called pools.

As streams aggregate, they form rivers that are sufficiently deep and usually sufficiently turbid that light does not reach the bottom. Algae mostly grow in the water column in rivers, so they are called phytoplankton; but benthic algae are also on the bottom in the shallow margins of rivers. In rivers, the benthic filter-feeders, collectors, and grazers continue to function across all or part of the river, and an additional group of small, largely neutrally buoyant animals, the zooplankton, accumulate and consume suspended algae and bacteria. In addition, another diverse group of aquatic invertebrates, the mussels, can develop in abundance and filter algae and organic matter from the water column of rivers. During low flow periods when water flows slowly and resides in the river for longer periods of time than high flows, phytoplankton and zooplankton can accumulate to high abundances, like those that would be observed in lakes.

Groundwater is a huge reservoir of freshwater, 0.75 % of all water and 30 % of all freshwater. The exchange of groundwater and surface water in streams is little appreciated. Water in streams originates from precipitation that either runs off the surface of the land or penetrates soils and discharges into streams from shallow or deep groundwater sources. The route of precipitation to the stream varies with porosity of soils. In sandy soils, large portions of precipitation percolates to deeper groundwater storage zones so that storms have relatively little effect of river discharge compared to shallow soils over bedrock and steep slopes, where runoff from the land surface causes great storm surges and floods. During low flow periods between storms, most water in streams and rivers originates from groundwater, and during this time, substantial proportions of water move between the ground and surface water zones.

The biodiversity and ecosystem processes of streams and rivers extend into gravels and sands below the bottom of the channel as a result of this exchange of groundwater and surface water, and sometimes to great depths depending upon porosity of the channel bottom. The zone below the stream bottom is called the hyporheos. It contains a great abundance of bacteria, fungi, and aquatic insect larvae. Recharge of groundwater from streams carries dissolved and particulate organic matter that nourishes the bacteria, fungi, and aquatic insect larvae that live in the hyporheos. There bacteria and fungi decompose organic matter and release inorganic nutrients. Evidence of decomposition in hyporheic zones can be seen on the downstream side of gravel bars where algae sometimes grow prolifically in the nutrient-rich groundwater that leaks back into the stream channel.

Decomposition of dissolved and particulate organic matter by bacteria and fungi, uptake of inorganic nutrients by decomposers and algae, and the filtering, collecting, and grazing of bacteria and fungi by aquatic insect larvae contribute to biogeochemical cycling and nutrient retention, which are major ecosystem services of streams and rivers. The organisms of streams transform and retain matter and energy within the river ecosystem in a process called spiraling, in which matter and energy cycles from stream bottom to water column and consequently flows downstream (Webster and Patten 1979). Consumption of decomposers, algae, and invertebrates by fish also helps retain matter in streams and rivers. Aquatic insect larvae emerge from streams as adults, fly upstream more than downstream, and many are consumed by birds, spiders, and other terrestrial predators. Floods scour organic matter (living and dead) from streams and deposit them in the flood plain. Headwater streams are particularly important in transformation and retention of nutrients and organic matter leaking from the landscape, because the volume of water in them is relatively small compared to the surface area of the channel.

Photosynthesis by algae and decomposers' utilization of terrestrial and aquatic sources of organic matter fuel stream and river ecosystems. Primary production, biogeochemical cycling, and nutrient retention are examples of intermediate EGS that regulate water quality and provide clean water for drinking, industrial and agricultural processes, and recreation. Some of the most fertile soils for agriculture are floodplains of rivers where organic matter from streams and rivers was deposited during floods. The in-stream processing of both nutrients and terrestrial inputs of organic matter prevents their transport to coastal zones where they could feed algal blooms. Fisheries of streams and rivers are also nourished by the food webs based on algal production and decomposers using terrestrial inputs. In many parts of the world, small fishes as well as large fishes are harvested for local consumption or support of local businesses that ship them far away. Thus, streams and rivers provide a diversity of intermediate services that have in-stream, floodplain, and downstream benefits, which lead to many final ecosystem services that provide direct benefits to humans (Boyd and Banzhaf 2007), such as drinking water, industrial and agricultural water supply, recreation, fisheries, biodiversity, and food crops.

Effects of Global Change on Ecosystem Goods and Services of Streams and Rivers

Climate change and human alterations of the surrounding landscapes will have complex independent and interactive effects on the EGS of streams and rivers. To resolve this complexity, it helps to consider the direct and indirect effects of global change on streams and rivers and then consider them independently and interactively. Human alterations have affected streams and rivers for millennia, but today, these alterations are globally distributed. Agriculture, urban development, and roads alter the physical and chemical structures of landscapes. They increase runoff, alter flashiness of stream hydrology, and increase erosion across the landscape and in the stream channel. They pollute streams with sediments, pesticides, toxic chemicals from industrial wastes, and nitrogen and phosphorus from fertilizers and wastes of humans and animals. Climate change will increase stream temperatures and the frequency of heavy rains and droughts. Heavy rains will exacerbate the problem with runoff of nutrients and sediments from the landscape and channel erosion during high flow events.

Sediment pollution reduces water clarity and habitat suitability for the bacteria, algae, and invertebrates and limits their contributions to EGS. Many stream bottoms have cobble, gravel, or sandy bottoms to which biota have adapted. Fine sediments from erosion bury these habitats and the microbes on them. Excess sediments on the stream bottom prevent growth of algae and bacteria; they alter motility and food sources for aquatic invertebrates as well. Sediments in the water column shade the bottom and clog the filter-feeding of aquatic insects. Thus, sediment pollution reduces the retention capacity of streams. Sediments then decrease biogeochemical cycling as well as productivity of the food web.

Nutrient pollution increases algal growth and overwhelms the capacity of the stream to retain nutrients. Increased growth of algae can alter biodiversity in streams by physically altering habitat structure in ways that affect which aquatic insects can live in the habitat. Algal photosynthesis during the day releases oxygen into the water. Algal and bacterial respiration uses the dissolved oxygen in the water. This produces diurnal fluctuations in dissolved oxygen with daytime highs and nighttime lows. Excessive algal growth also supports more bacteria in streams. As algae and bacteria accumulate, the fluctuations increase sufficiently that nighttime dissolved oxygen gets so low that many organisms, particularly fish and aquatic insect larvae, cannot survive.

Human activities have heavily altered the natural flow regimes of rivers with dams, groundwater withdrawals, stream channel dredging, groundwater withdrawals, and impervious surfaces. These flow alterations profoundly alter biodiversity and ecosystem functions (Poff and Zimmerman 2010; Sabater 2008). Channels of streams and rivers are carved by the power of water moving through them, so changes in the frequency and intensity of high and low flow events alter physical structure and resulting chemical and biological conditions. Increased impervious surfaces (roads, roofs, parking lots) increase the rate at which rain reaches streams; this increases peak flood flows that cause greater bank erosion and sediment deposition in channels. Dams are constructed for hydropower and water storage providing irrigation, drinking water, and flood control, but they threaten biodiversity by blocking migration of fish to upstream habitats which are commonly breeding habitat. Groundwater withdrawals for irrigation, hydrologic fracturing, and drinking water supply can deplete surface water flows, habitat area, and stream temperature by changing groundwater:surfacewater ratios in channels. Dredging stream channels reduces habitat diversity, reduces flow resistance in channels, and increases downstream flooding. Headwater streams have been buried and channelized with agricultural and urban development, which reduces or eliminates their capacity for waste uptake and retention. Reduced flood flows in channels below dams allow sediments to accumulate long enough that trees and shrubs encroach on channels as they spread across gravel bars. So, human alterations of stream and river hydrology complexly affect EGS, increasing some and decreasing others.

Increases in air temperature will increase water temperature, which affects dissolved oxygen and the kinds of organisms that can live in the streams. Kaushal et al. (2010) show that stream temperatures across North America have increased by 0.009–0.077 °C year^{-1} with the greatest increases in urban areas. The capacity for water to hold dissolved oxygen decreases as water temperatures rise, such that 100 % saturation of water with dissolved oxygen will decrease about 1 ppm with a 4 °C increase in water temperature. In addition, metabolism of organisms tends to increase with temperature across most ranges of temperatures in streams, so metabolic demand for oxygen will increase and the capacity of water to hold oxygen will decrease with global warming, which will further exacerbate low oxygen problems. Low dissolved oxygen is one of the major threats to biodiversity and ecosystem functioning in rivers and streams.

Temperatures have strong direct effects on the species of aquatic insects, fish, and algae that can live in streams. In general, metabolism of organisms increases with temperature until it reaches an optimum, above which temperature reduces efficiency of metabolic processes. Thus, species have an optimum temperature range with upper and lower tolerances to changes in temperature. One of the major effects of global warming on final ecosystem services will be transformation of trout fisheries into warm water fish habitat. For example, Hari et al. (2006) found that brown trout populations have already started to decline in alpine rivers of Europe. Climate change will also have profound effects on water delivery to rivers and streams.

Regional variations in warming will affect precipitation and flow in rivers and stream such that precipitation and flow will increase in some regions and decrease in others. Changes in precipitation by climate models can simulate observed patterns in long-term stream flow (Milly et al. 2005). When models of future climate change and streamflow are linked, they indicate 10–40 % decreases in rivers in western North America, northern and southwestern South America, western and southern Africa, southern Europe, the Middle East, and Western Asia (Fig. 32.2). They also predict 10–40 % increases in flows in northern North American, Europe, and Asia, northwestern and southeastern South America, north central and eastern Africa, and southern Asia. Lehner et al. (2006) used an integrated water model called WaterGAP to simulate high and low flow conditions under future climate change scenarios. They determined that events with an intensity of today's 100-year frequency of occurrence would occur as often as 10–50 years by the 2070s. In addition, global warming is melting glaciers and snowpacks, which strain water supply during the summer when it is most needed for drinking and crop irrigation. Stewart et al. (2004) estimated peak runoff in snowmelt-dominated systems, like mountain streams, will occur 30–40 days earlier than today.

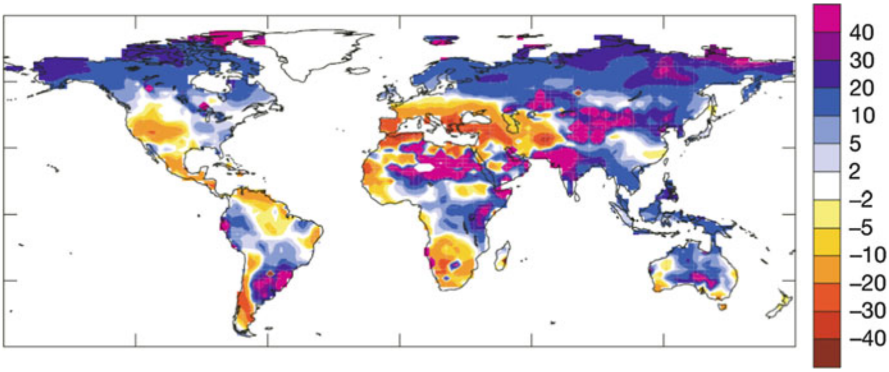

Fig. 32.2 Mean relative percentage change in flows predicted for the twenty-first century (Milly et al. 2005)

Thus, many areas will be threatened with increased flooding as others are threatened by increased droughts and water scarcity. Palmer et al. (2008) estimate that 13 % of the world's large river basin area, 7 % of the entire world's area when summed, will suffer from water scarcity, and nearly one billion people live in those areas.

Problems with water scarcity may be exacerbated by vulnerability to decreases in water quality and other EGS. Increases in flood intensity and drought duration in combination with global warming could cause greater problems with algal blooms and threats to drinking water supply (Paerl and Huisman 2008). Nutrient runoff with floods is expected to increase with expected storm intensity with global warming. When droughts follow floods during warm periods of the year, water retention time in rivers should increase and enable greater algal blooms. In combination with flood flows introducing nutrient loading, increased water retention time with droughts should provide a longer time for algae to accumulate, sequester available nutrients, and cause problems with low oxygen, biodiversity, and drinking water supplies. Stable water column conditions can occur in large rivers at low flow which favors accumulation of cyanobacteria, which can produce toxins. Algal blooms also affect drinking water by causing taste and odor problems and by producing precursors for toxic chemicals, such as trihalomethanes that develop during disinfection of drinking water.

Climate change will drive land use changes as agriculture moves to higher latitudes where climate will be sufficiently warm to grow crops. Population density, nutrient loading, and accompanying diverse demands and threats to streams and rivers will move with agriculture. Many areas today are suffering great losses in agricultural sustainability as ground waters are extracted for irrigation faster than they can be replenished. As these areas are further degraded, demand for other marginal lands will increase. Thus, new regions will be altered as agriculture migrates toward higher latitudes, new rivers and streams will be exposed to the stressors of agriculture and accompanying urban development, and abandoned landscapes and water resources will remain scarred and require long periods for recovery.

When threats to EGS such as water quantity, quantity, and biodiversity are combined, nearly 80 % of the world's population is exposed to problems of water security and biodiversity (Vörösmarty et al. 2000). Solutions to problems exist, but mitigation of impacts and adaptation to water demands by agriculture and growing urban populations require great investments in infrastructure, which leaves many poorer societies vulnerable (Vörösmarty et al. 2010). Ecosystem restoration costs much more than stressor management before impacts have occurred. Management will be challenged, because real tradeoffs exist in managing in-stream conditions and watersheds. Some alterations of ecosystems, such as dams and aquaculture, increase services provided by rivers for irrigation and food production, but negatively affect other in-stream and downstream uses. Prioritizing management of pollution, biological invasions, dams and river fragmentation to protect EGS will require rigorous quantitative understanding of relationships among them and spatial optimization in ways that protect critical EGS in locations where they remain and restore them in locations most in need or requiring the least investment. Future climate and land use change will complicate management, which increases the need to act now.

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► Impacts of Projected Changes in Climate on Hydrology
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► Threats to Freshwater Biodiversity in a Changing World

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