Chapter 20
Drivers and impacts of changes in aquatic ecosystems
About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon’s ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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Graphical Abstract

Figure 20.A Graphical Abstract
Drivers and Impacts of Changes in Aquatic Ecosystems

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Key Messages

- Over the last four decades, and especially over the last two, many Amazonian aquatic ecosystems have become less connected and more polluted.
- Prior to the massive impacts of dams built over the past four decades, overexploitation of plant and animal species was the most significant factor causing aquatic ecosystem degradation in the Amazon Basin. This degradation continues to advance.
- The spatial distribution of impacts on biodiversity and ecological processes is uneven.
- Agricultural and industrial waste and sewage contaminate Amazonian waters.
- Mercury contamination from gold mining (legal or not) is a major environmental and public-health concern.
- Hydroelectric dams block fish migrations and the transport of sediments and associated nutrients, as well as altering river flows and oxygen levels.
- Deforestation greatly affects the physical and chemical characteristics of watercourses and when agriculture replaces forests can release fertilizers, herbicides, and other pollutants into the water, as well as sediments from soil erosion.
- Petroleum extraction and resulting oil spills can have catastrophic impacts on aquatic ecosystems.
- The biological productivity of aquatic ecosystems is affected both downstream and upstream of these impacts.

Abstract

The Amazon’s aquatic ecosystems are being destroyed and threats to their integrity are projected to grow in number and intensity. In this chapter we review a number of these threats. Hydroelectric dams (307 existing or under construction) have changed almost every aspect of Amazonian aquatic ecosystems, and many more dams are planned (239), posing threats to the region’s enormous aquatic biodiversity and fisheries resources. By blocking fish migrations dams affect important commercial species, as well as the flow of sediments and nutrients that sustain aquatic food chains and support fish populations. By altering stream flows and flooding regimes, dams and their reservoirs also disrupt downstream ecosystems.

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including flooded forests and the floodplain lakes that are essential for breeding of many fish species. The low-oxygen (anoxic) conditions found near reservoir bottoms cannot be tolerated by many fish species. They also favor the formation of highly toxic methylmercury and the production of methane, a powerful greenhouse gas. Small dams and reservoirs can have substantial impacts that are often even greater than large dams on a per-Megawatt (MW) or per-hectare basis. In Brazil the definition of “small” dams has progressively increased from less than 10 to 30 to 50 MW, opening an expanding loophole in the environmental licensing system. Overharvesting of fish for both food and the ornamental trade has depleted fish stocks and altered their ecological roles. Native species are threatened by invasive species that escape from aquaculture operations and potentially from proposed inter-basin river diversions. Deforestation changes the chemical and physical properties of streams, including releasing natural deposits of heavy metals (such as mercury from erosion) and eliminating aquatic species that inhabit watercourses in Amazonian forests. Pollution sources include toxins from agriculture and industrial and urban waste, such as plastic; mercury; transition metals like Cu, Cd, Pb, and Ni; urban sewage; and various forms of toxic waste. Oil spills have had disastrous consequences in Ecuador and Peru. Gold mining releases large amounts of sediments, in addition to releasing mercury and provoking the clearing and degradation of floodplain forests. Roads contribute to the fragmentation of streams and river tributaries as well as generating sediments through soil erosion, in addition to the sediment from the deforestation that roads provoke. Navigational waterways cause multiple impacts on rivers converted to this use, particularly affecting the reproduction habitats of freshwater species. Climate change impacts aquatic ecosystems through increased temperature and extreme droughts and floods. Interactions among drivers mean many of these impacts are even more harmful to aquatic ecosystems. The authors of this chapter recommend that no more hydroelectric dams with installed capacity ≥10 MW be built in the Amazon, that investments in new electricity generation should be redirected to wind and solar sources, and that all environmental assessments should incorporate synergistic and cumulative impacts in their analyses. In addition to the ecosystem impacts that are the subject of this chapter, the extraordinarily great social impacts of Amazonian dams (Chapter 14) lead to the same conclusion. Fortunately, countries like Brazil have abundant undeveloped wind and solar potential.

Keywords: Climate change, dams, fish, invasive species, mercury, oil spills, pollution, river diversion, toxic waste, waterways

20.1 Introduction

The Amazon’s rivers and streams reflect the landscapes through which they flow. The great Amazon limnologist Harald Sioli (1984) explained that “The big rivers receive their waters from a dense network of Igarapés, streams and brooklets. The total length of their courses exceeds more than a thousand times that of the Amazon; this implies an intimate contact of the Amazon aquatic system with its terrestrial surroundings and a determining influence of the latter on the chemistry and biology of the small watercourses.” This influence reflects not only geological differences such as those that produce the region’s white-, black- and clear-water rivers, but also the effects of human activity. These watercourses are often compared to a person’s blood or urine - the subject of medical testing to identify problems in a human body. In the same way, the deteriorating health of a terrestrial or aquatic ecosystem will be reflected in the quality and quantity of the water flowing from its hydrographic basin.

The sheer magnitude of the flows in the Amazon reflect the region’s global significance, annually discharging 6.6 trillion cubic meters of fresh water to the oceans, along with 600-800 million tons of suspended sediments (Filizola and Guyot 2011). The Amazon’s aquatic biodiversity is also globally significant. So far, 2406 fish species have been described (Jézéquel et al. 2020), although hundreds
more remain to be described such that the actual number is likely to be above 3,000 species (Val 2019). Described floodplain tree species total 918 (Wittmann et al. 2006). As mighty as the Amazon River is, its aquatic ecosystems are also fragile (e.g., Castello et al. 2013a). The multiple threats these ecosystems face are the focus of this chapter.

Amazonian rivers and streams connect distant parts of the vast Amazon Basin, and impacts originating at any given location may be felt thousands of kilometers away. A dam altering downstream sediment flows, for example, can affect ecosystems all the way to the Atlantic Ocean and even in the Amazon’s estuary. Likewise, a dam blocking migratory species causes upstream effects reaching all the way to the Amazon’s headwaters in the foothills of the Andes. The same is true for other drivers of change in freshwater systems (Figure 20.1); overharvesting of fish stocks (both commercial and ornamental species) can disrupt aquatic food webs; introduction of invasive species can disturb native species communities, causing habitat loss; and deforestation can alter water quality, temperature, and climate at various scales. Water pollution (e.g., agricultural and industrial wastes, plastics, medicines, oil spills, and transition metals such as mercury) can have widespread and cumulative effects, as can infrastructure such as dams, roads, river diversions, and waterways. Other factors include urban and industrial growth, agriculture, and regional climate change. These drivers have synergistic interactions among themselves and, when acting together, can amplify each other’s impacts (Costa et al. 2011; Anderson et al. 2018; Athayde et al. 2019; Castello and Macedo 2016; Silva et al. 2019). The construction of dams, for example, inevitably results in the construction of roads, which in turn may increase deforestation for pasture and commodity crops such as soy (Fearnsidge 1989; Guerrero et al. 2020). These land-use changes ultimately result in the pollution of rivers and streams, be it from the large-scale use of fertilizers and agricultural chemicals, the formation of toxic methylmercury in reservoirs, or rapid population growth from migration spurred by dam construction. These multiple impacts on aquatic ecosystems threaten the Amazon’s enormous aquatic biodiversity, as well as the health and well-being of many Amazon residents who depend on fisheries and other aquatic resources for their livelihoods (see Chapter 21).

Aquatic systems in the Amazon are environmentally diverse and include many characteristics that can pose unique challenges for aquatic organisms. Among these are habitat heterogeneity, different river types (such as white-, black- or clear-water), and dramatic seasonal flood events (i.e., flood pulses) when rivers overflow their banks and invade adjacent forests, creating habitats such as várzeas (white-water floodplains) and igapós (black-water swamps) that are essential for feeding and nurturing fish (Barletta et al. 2010). Water-quality indicators, such as dissolved oxygen, temperature, electrical conductivity, and pH, may also vary seasonally and spatially depending on the drainage area (e.g., the Andes, Guiana, and Brazilian shields), requiring aquatic organisms to adjust to changing conditions. These challenges have favored the evolution of adaptive strategies at all levels of biological organization (Junk et al. 1989; Campos et al. 2019; Val 2019; Piedade et al. 2000). Fish and other aquatic animals have evolved strategies to cope with extreme environments (e.g., water with low oxygen, high acidity, low ion concentrations, and high temperatures) and high seasonal variability in food resources, resulting in high biotic diversity (Val et al. 2006; Val and Almeida-Val 1995; Zuanon et al. 2005).

Interactions between extreme habitat conditions and anthropogenic disturbance are driving many organisms to their physiological limits; adaptations to their natural environment do not always promote survival under anthropogenic stresses. An emblematic example is the effect of oil spills on fish. Among the many strategies Amazonian fish have developed to cope with low oxygen is the ability exploit the water-air interface that, in the case of an oil spill, increase their contact with pollutants concentrated at the top of the water column.
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The interactions among the different drivers of degradation in aquatic systems are summarized in Figure 20.1. This chapter begins with a discussion of hydroelectric dams because of their very large and diverse impacts in the region, and the many connections between dams and other drivers of change in aquatic ecosystems. It then reviews the effects of overharvesting, invasive species, pollution, mining, roads, river diversions, waterways, and climate change on Amazon aquatic systems. The chapter concludes with a discussion of synergistic effects among drivers, followed by conclusions and recommendations.

20.2 Infrastructure

20.2.1 Dams

20.2.1.1 Existing dams and future plans

We identified 307 dams that exist or are under construction and 239 that are planned or projected (Figure 20.2). These numbers vary in the literature (Finer and Jenkins 2012; Lees et al. 2016; Almeida et al. 2019) due to differences in the areas covered, inconsistent definitions of what constitutes a “planned” dam (especially for small dams), and variable information across the eight countries and one overseas territory comprising the Amazon Basin. Plans for future hydroelectric dams are also continually in flux.

“Small” dams have less hydrological impact than large dams in absolute terms, but relative to their installed capacity for energy generation they have a significantly greater impact (Timpe and Kaplan 2017). Since 2016, “small” hydroelectric dams have been defined in Brazil as those with less than 50 MW of installed capacity; the limit was 30 MW from 2004 to 2016, and 10 MW before 2004. Dams in this category are exempt from federal environmental licensing and can be built with (generally less-rigorous) state licensing, thus motivating both the expansion of this loophole by redefining “small” dams and a rapidly increasing number of “small” dams in the Brazilian Amazonia. The definition of “small” dams varies widely among countries, with 10 MW being “increasingly recognized as the international standard” (Couto and Olden...
Figure 20.2 Existing and planned hydroelectric dams and waterways in the Amazon. Currently there are 307 dams existing or under construction, and 239 planned or projected (total = 546).
20.2.1.2 Fish communities

Hydroelectric dams negatively impact fish communities both above and below the reservoir due to habitat loss and severe changes in the hydrological regimes of flooded forests (Ribeiro and Petere 1988; Ribeiro et al. 1995; Santos et al. 2018). The conversion of a stretch of river from running water (lotic) to still water (lentic) either eliminates or greatly reduces the populations of many species, few of which are adapted to the new environment (Agostinho et al. 2016). Fish communities become structurally and functionally different from the pre-dam baseline (Araújo et al. 2013; Arantes et al. 2019a, b), with one of the most evident impacts being the impediment of both upstream and downstream migration (Pelicice et al. 2015a). Only some of the highly diverse migratory fish species are able to use fish passages (Pelicice and Agostinho 2008). The famous “giant catfish” of the Madeira River (Brachyplatystoma spp.) is among those that have not been able to use the passages in the large Santo Antônio and Jirau Dams in the Brazilian Amazon, although they are physically able to climb the passages if placed inside them (Figure 20.3). This is because the instinct of the fish during their annual migration to spawn in the headwaters is to swim up the main channel of the river, not to enter small streams like the ones imitated by the passages. Although not yet documented for the Amazon, basin-wide extirpations of migratory species have occurred in many rivers of the world due to ineffective fish ladders (see Pringle et al. 2000; Freeman et al. 2003). Amazonian dams and their ineffective fish passages have already seriously disrupted the migration routes of many fish species, resulting in declining fisheries both above and below the dams and in changes in assemblage structure and functional traits of fish communities (review in Duponchelle et al. 2021). Ineffective fish ladders in the Amazon have caused declines of migratory species at the Santo Antônio Dam on the Madeira River in Rondônia (Hauser et al. 2019) and the Lajeado Dam on the Tocantins River in the state of Tocantins (Agostinho et al. 2007, 2012). In other cases, no fish passage was provided, as at the Coarace Nunes Dam on the Araguarí River in Amapá (Sá-Oliveira et al. 2015a), the Samuel Dam on the Jamari River in Rondônia (Santos 1995), and the Tucuruí Dam on the Tocantins River in Pará (Ribeiro et al. 1995). The resulting loss of fisheries has severe social impacts.

20.2.1.3 Aquatic mammals, reptiles, amphibians, and insects

Many other aquatic taxa are affected by hydroelectric dams (Lees et al. 2016). For example, dams can cause the fragmentation of populations of dolphins, amphibians, and reptiles (especially larger ones such as caimans and turtles). Dams can also affect these animals indirectly – e.g., they can decrease prey availability for dolphins (Salisbury 2015; Araújo and Wang 2015). Population fragmentation by dams disrupts gene flow and can result in small and therefore vulnerable populations (Gravena et al. 2014; Paschoalini et al. 2020).

The beaches on which turtles often lay their eggs are commonly flooded by dam-altered hydrology (Alho 2011). This occurs not only in the reservoir...
area itself (Norris et al. 2018), but also in downstream areas where water levels vary depending on power generation (Salisbury 2016). A number of planned dams are particularly threatening to turtles (Gonzales 2019). For instance, on the Rio Branco in Roraima the planned Bem Querer Dam (Fearnside 2020a) is likely to impact downstream turtle breeding beaches (e.g., Nascimento 2002). On the Trombetas River in Pará, the dam that is planned to be the centerpiece of the Barão do Rio Branco Project announced by Brazil’s current presidential administration (The Intercept 2019) would be just upstream of one of the Amazon’s largest turtle-breeding beaches, the “tabuleiro do Jacaré” (e.g., Forero-Medina et al. 2019; Zwink and Young 1990).

In a study of frogs at the Santo Antônio Dam on the Madeira River, the composition of species assemblages present near the natural river margin before reservoir flooding did not re-establish on the new margin up to four years after the reservoir was filled (Dayrell et al. 2021). Frog species richness near the new margins increased by 82% one year after filling, but this percentage had declined to 65% by four years after filling and showed “no tendency to return to the original assemblage.”

Dam impacts on aquatic insects vary; species that depend on fast-moving water lose habitat with the creation of reservoirs and thus decrease in abundance; while others that breed in the standing water of a reservoir, such as mosquitos, can undergo population explosions. At the Tucurui Dam, in Brazil’s Pará state, up to 39% of the reservoir was covered by macrophytes (aquatic plants) in the first years after impoundment (Lima et al. 2000), providing breeding sites for mosquitos in the genus *Mansonia* (Fearnside 2001). The resulting “mosquito plague” caused many of the people who had been resettled near the reservoir to abandon their lots and initiate a new hotspot of deforestation elsewhere (Fearnside 1999). Conversely, *Anopheles* mosquitos (the vectors of malaria) diminished in abundance after completion of the Tucurui Dam (Tadei et al. 1991). At the Samuel Dam (in Brazil’s state of Rondônia) *Culex* mosquitos exploded dramatically and *Anopheles* mosquitos, which were already abundant before construction of the dam, are also believed to have increased (Fearnside 2005) (Chapter 21).

Alteration of flows downstream of dams can also impact aquatic insects drifting in the water (Castro et al. 2013; Patterson and Smokorowski 2011) and those that inhabit the edges of the river, such as mayflies (Ephemeroptera) (Kennedy et al. 2016). Changes in substrate composition (i.e., from coarse to fine substrates) downstream of dams is also known to negatively affect aquatic insects (Wang et al. 2020).

### 20.2.1.4 Reservoir stratification

Reservoirs commonly stratify into layers with colder water at the bottom and a division (thermocline) at 2-10 m depth separating the warmer and colder layers. Water does not mix between the two layers. Oxidation of organic material at the bottom consumes oxygen to produce CO₂ until oxygen is no longer available, after which decomposition must end in methane (CH₄). Stratification is essentially universal in storage dams such as Tucurui on the Tocantins River (Figure 20.4). In run-of-river dams, stratification will depend on the velocity with which the water moves through the reservoir. In run-of-river dams where the main channel remains free of stratification, as at the Santo Antônio Dam on the Madeira River, bays and flooded tributaries can still stratify (Fearnside 2015a).

Underwater biomass decomposition leads to the emission of both CO₂ and CH₄. One ton of methane has an impact on blocking the passage of infrared radiation that is 120 times that of a ton of CO₂ while it remains in the atmosphere (Myhre et al. 2013). If we are to stay within either of the Paris Agreement’s limits (mean global temperature “well below 2°C” or below 1.5°C above the preindustrial mean), then the impact of CH₄ in terms of CO₂-equivalents must be considered on a 20-year basis, which essentially triples the impact of hydroelectric dams on global warming (Fearnside 2015b, 2017a,b). The impacts of different green-
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House gases are expressed in terms of CO$_2$ equivalents based on global-warming potentials (GWPs), which represent the effect on global temperature over a given time horizon from emitting one ton of the gas relative to the simultaneous emission of one ton of CO$_2$. Considering the 20-year GWPs from the IPCC’s 5th Assessment Report, 25% of lowland dams would emit even more CO$_2$ equivalents per megawatt-hour generated than a coal-fired power plant, and 40% of them would emit more than generation from natural gas (Almeida et al. 2019). The result would be even worse for Amazonian dams if emissions from the water passing through the turbines and spillways were included in these calculations. Box 20.1 explains the contribution of Amazonian dams to greenhouse-gas emissions.

Considerable uncertainty exists in calculating greenhouse-gas emissions (i.e., CO$_2$, CH$_4$ and N$_2$O) from dams on the scale of the Amazon as a whole. There is much variation from dam to dam with reference to key variables such as the depth of water at the intakes of the turbines and spillways, the average turnover time of water in the reservoir, and the existence of bays and other areas in the reservoir where turnover times are much longer than the average (Fearnside 2013a, 2015a). For example, run-of-river dams emit less than storage ones because they have smaller reservoirs with faster water turnover times and less variation in water level. However, run-of-river dams can still emit methane even if the water flow is sufficient to prevent stratification in the main channel of the river because the tributaries and bays stratify, and methane produced in them reaches the spillways and turbines to be emitted downstream (Fearnside 2015a; see also Bertassoli Jr et al. 2021). Another key aspect in the variation in dam-related emissions is dam location; lowland dams (eleva-
BOX 20.1 Greenhouse-gas emissions from Amazonian dams

Greenhouse-gas emissions from Amazonian dams include both methane produced in stratified reservoirs and CO$_2$ from trees killed by flooding (Figure B20.1). The dead trees subsequently decay and release greenhouse gases (i.e., Abril et al. 2013; Fearnside 1995, 2002a, 2005). In addition, trees near the edges of reservoirs suffer stress from the high water table, causing mortality (dos Santos Junior et al. 2013, 2015; Fearnside 2009). The large amount of initial biomass when a reservoir is flooded (which is especially high in tropical forests), in addition to the presence of easily oxidized labile carbon in the soil, leads to young reservoirs being larger emitters than older ones (Barros et al. 2011). After these carbon pools are depleted, emissions decline but do not fall to zero (Fearnside 2009, 2016).

Figure B20.1 Some of the approximately 100 million trees (diameter > 10 cm) killed in the shallow reservoir behind the Balbina Dam. The light-colored trees are dead. The reservoir has over 3,000 islands (bottom panel), increasing the impact on emissions from tree mortality, as well as the fragmentation impact on terrestrial fauna. Source: Fearnside 1989. Photographs: Philip Fearnside.
tion <500 m) produce more than triple the emissions per megawatt-hour generated than dams at higher elevations (Almeida et al. 2019). Similarly, tropical dams have higher emissions than those at higher latitudes (Barros et al. 2011). Because a substantial amount of information is needed about each dam in order to estimate greenhouse-gas emissions, it is difficult to make valid regional, national, or global estimates. Simple extrapolation based on installed capacity, which has been done in various global estimates, is insufficient.

Emissions resulting from the reservoir surface tend to be the only ones considered when evaluating the impacts of dams on climate change, which greatly underestimates total dam emissions (e.g., Brazil 2004). Reservoir surfaces can emit gases both by diffusion and by bubbling (ebullition). Diffusion is a large source in the first two years after reservoir filling, but subsequently declines in importance (Dumestre et al. 1999). Bubbling is greater in shallow parts of the reservoir, and it occurs at irregular intervals, with short periods of intense bubbling interspersed with long periods with few bubbles (Lima 2002). The treatment of these effects in calculating annual emissions from a reservoir can have dramatic effects on the calculated impact (Pueyo and Fearnside 2011; Fearnside and Pueyo 2012). The often-neglected emissions from turbines and spillways (“downstream emissions”) are critical (Fearnside 2013a, b, 2015a). Downstream emissions, which are largely proportional to water flow, are generally greater than those from the reservoir surface, which are proportional to reservoir area. This is the case of the Petit Saut Dam in French Guiana, which has much more data on emissions than any other Amazonian dam (Delmas et al. 2001; Abril et al. 2005). In Balbina, which has a large reservoir and little water flow, surface emissions are slightly larger than downstream emissions, whereas in Tucuruí, which has approximately the same reservoir area as Balbina but much more water flow, downstream emissions predominate (Fearnside 2002a; Kemenes et al. 2007, 2011, 2016).

In the first years after impoundment there is normally an explosion of floating and rooted aquatic plants (macrophytes) due to a flush of nutrients in the water when the soil and litter are first flooded and from leaves dropped by dying trees. The macrophytes add to the oxygen depletion provoked by decay of the flooded vegetation. The macrophyte cover subsequently declines to lower levels, as occurred at Tucuruí and Balbina (Fearnside 1989, 2001). Lower oxygen content in a reservoir as compared to the running water of the natural river is one of the changes that cause populations of most of the original fish species to either disappear or be reduced to minimal levels, being replaced by a different and less-diverse assembly of species (Sá-Oliveira et al. 2015a,b).

20.2.1.5 Alteration of sediment flows

Dams reduce sediment flows by retaining sediments in reservoirs (Fearnside 2013c). Downstream, reduced sediment load results in scouring, where erosion of the riverbanks and bottom accelerates (Santos et al. 2020). Reduction in sediment flow deprives the downstream river of the nutrients associated with sediment particles. In the Madeira River, sediment transport downstream of the Santo Antônio and Jirau Dams decreased by 20% compared to pre-dam quantities (Latrubesse et al. 2017), which may have contributed to the observed sharp decline in fish catches downstream of the dams (Lima et al. 2017; Santos et al. 2020). Because suspended particulate organic matter and aquatic macrophytes are the base of the food chain of the lower Amazon (Arantes et al. 2019c), reduction of sediment loads by Andean dams are likely to have far-reaching consequences for aquatic food webs by reducing nutrient supplies and thereby affecting primary production (Forsberg et al. 2017). Along with reduced oxygen, reduced nutrient flows may have contributed to the collapse of fish and freshwater shrimp populations below the Tucuruí Dam (Odinetz Collart 1987), an impact these populations have never recovered from (Cintra 2009).
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Reducing sediment flows also impacts aquatic biota by modifying river geomorphology. Andean tributaries provide over 90% of the sediment budget of lowland rivers in the Amazon Basin (Filizola and Guyot 2009), playing critical roles in geomorphological processes such as river meandering and floodplain formation (Dunne et al. 1998; Meade 2007; McClain and Naiman 2008; Constantine et al. 2014). Interfering with these processes disrupts the lateral connectivity between river channels and floodplains and ultimately reduces fish yields (Forsberg et al. 2017; Almeida et al. 2020). The fishes’ seasonal use of floodplains has essential nursery and feeding roles (Bayley 1995; Nilsson and Berggren 2000; Castello et al. 2015; Hurd et al. 2016; Bayley et al. 2018).

Impacts from reduction of sediment flows are especially problematic in white-water rivers. In some cases, the process of dam construction can have the opposite effect of temporarily increasing sediment loads in clear-water and black-water rivers, which is also damaging. In either case, dam-induced downstream modifications affect fishes’ longitudinal upriver spawning migrations (Agostinho et al. 2004, 2008; Lytle and Poff 2004; Bailly et al. 2008). These migrations are affected by modifying the physical and chemical cues to which fish have adapted (Freitas et al. 2012; McIntyre et al. 2016; Timpe and Kaplan 2017). This impact is in addition to the catastrophic effect of physical blockage of migration routes by dams.

20.2.1.6 Alteration of streamflow

Storage dams can cause downstream flow changes over longer periods than run-of-river dams, but the large variation in daily or hourly time scales for run-of-river dams can also provoke significant changes in streamflows (Almeida et al. 2020). Alteration of flow patterns in the river below a dam has multiple effects on downstream ecosystems. Timpe and Kaplan (2017) related ecological impacts to hydrological measures within four groups of hydrological parameters: 1) frequency and 2) duration of high and low pulses (flood pulses), and 3) the rate and 4) the frequency of water condition (level) changes. Other impacts on streamflow occur when the reservoir is filling, such that downstream river stretches dry out during all or part of the filling period. The Balbina Dam was an extreme case, with flow stopped for over a year (Fearnside 1989). The Belo Monte Dam produces a similar effect that is permanent and on a grand scale; water flow is greatly reduced in a 130-km stretch known as the “big bend of the Xingu River” (Volta Grande do Rio Xingu), with 80% of the river’s annual flow diverted (Figure 20.5).

Modifications in the hydrological regime directly impact aquatic biodiversity. Fish behavior, especially as related to migration and reproduction, is attuned to flow changes, and false signals caused by dams can induce fish to behave in ways that jeopardize their reproductive success (Agostinho et al. 2004; Bailly et al. 2008; Freitas et al. 2012; Vasconcelos et al. 2014; Nunes et al. 2015; McIntyre et al. 2016). Reduction in water flow also negatively affects ornamental species, such as the zebra pleco (Hypancistrus zebra), which is threatened with extinction in the wild due to the Belo Monte Dam (Gonçalves 2011). In addition, alteration of flow and of river stages (height of the water level) can also affect turtle reproduction on river beaches, as is reported by Indigenous people for beaches below the Teles Pires and Sào Manoel Dams in the Tapajós Basin.

Flooded forests are impacted by the construction of mega-dams by increasing tree mortality due to extreme flooding (Resende et al. 2019; Oliveira et al. 2021). In the Uatumã River below Brazil’s Balbina Dam, streamflow alterations resulted in the death of 12% of the swamp (igapô) forest along a 125-km stretch of river below the dam (Assahira et al. 2017; Schöngart et al. 2021). During years with high rainfall the water level no longer reaches the minimum of the natural river, leaving trees in low topographic positions underwater beyond their tolerance limits (Figure 20.6).
Figure 20.5 The Belo Monte hydroelectric project has diverted water from the “Volta Grande” (big bend) of the Xingu River, a 130-km stretch between the two dams that comprise the project. Source: Watts (2019). Photograph: Fábio Erdos/The Guardian.

Figure 20.6 Ígapó (black-water swamp forest) killed by alteration of water levels downstream of the Balbina Dam. Photo: Jochen Schöngart, INPA.
20.3 Roads

Amazonian roads are often built without adequate passages for water, such as culverts or bridges, which results in the fragmentation of small tributaries and seasonal streams. Roads can act as dams, and their impact is especially strong for seasonal streams, with roads causing ponding along the road, blocking the passage of aquatic life and disrupting stream connectivity. On Brazil’s BR-319 (Manaus-Porto Velho) highway such blockages impede the seasonal migration of stream fishes (Stegmann et al. 2019). Roads also influence water quality and sediment deposition in aquatic systems. A study of 82 of the 242 points at which watercourses intersect BR-319 showed higher water turbidity downstream, as compared to upstream, of the road crossings (Maia 2012). A road without accompanying deforestation in Brazil’s state of Amazonas resulted in sediment from erosion of the roadbed and from dust raised by truck traffic that had notable effects on the community of aquatic insects in nearby streams, reducing richness and density in all functional groups, especially shredder species (Couceiro et al. 2011). One factor contributing to this is the burial of fallen leaves under the sediments, making these unavailable to insects in the shredder functional group (Couceiro et al. 2011). This reduces an important input to the base of the trophic pyramid in the aquatic ecosystem.

20.4 Navigational waterways and river diversions

Navigational waterways (Figure 20.7) have severe impacts on aquatic ecosystems. One is the dynamiting and removal of rocky habitats in order to allow barges to pass unimpeded. Many species of fish are endemic to these habitats and could go extinct when they are removed (e.g., Zuanon 2015). The planned removal of the extensive rock outcrops of the Pedral do Lourenço upstream from Marabá on the Tocantins River in the Brazilian Amazon would have these effects on a large scale (Higgins 2020).

In addition to removing rock outcrops, dredging of river channels to ensure yearlong navigability results in deepening shallow zones and removing woody debris (Castello et al. 2013a) that can hold rich, endemic fish fauna (Hrbek et al. 2018). Populations of these species are unlikely to recover once their specific habitat has been removed. In the Peruvian Amazon a project has recently been contracted for implanting the roughly 2,700-km Hidrovía Amazónica (Anderson et al. 2018; Bodmer et al. 2018). Recent field data on fluvial sediment movements and fish biodiversity in the Marañon and Ucayali Rivers in the Peruvian Amazon suggest that the Hidrovía Amazónica project could significantly alter river-channel morphology and consequently impact fish diversity and productivity on which local economies depend. Measurements of sediment transport in these rivers have shown that the filling time of the riverbed is very fast, with an average transport of 1.3 million tons of total sediments per day (Centro de Investigación y Tecnología del Agua CITA 2019). Among the most critical impacts that the Hidrovía Amazónica would cause to the Peruvian Amazon’s fish biodiversity, habitats, and fishery resources are (i) contamination of rivers due to fuel and oil spills from dredging vessels, (ii) disturbance of local and regional fish migrations, (iii) impact on fish spawning and refuge habitats, (iv) impact on the abundance of fish populations, (iv) mortality of fish eggs, larvae, and juveniles, (v) disturbance of the natural floods along the river banks, and (vi) impacts on fish productivity (García-Villacorta 2019). Other potential consequences are the degradation or destruction of breeding and feeding grounds, particularly for detritivorous species.

20.5 Overharvesting

20.5.1 Aquatic fauna harvested for human consumption

The unsustainable exploitation of plant and animal species has long been a significant factor in degrading aquatic ecosystems in the Amazon Basin (Castello et al. 2013a, Chapter 15). Most large, high-valued fish species, such as the giant pira-
Figure 20.7 Existing and planned waterways across the Amazon biome. Sources: Fearnside 2002b, 2014a; Mariac et al. 2021
ru or paiche (Arapaima spp.), which is already on the CITES II list of endangered species (Castello and Stewart 2010; Castello et al. 2015), the large fruit-eating tambaqui or gamitana, Colossoma macropomum (Isaac and Ruffino 1996; Campos et al. 2015), and many of the largest catfishes (e.g., Isaac et al. 1998; Ruffino and Isaac 1999; Petrere et al. 2004; Alonso and Pirker 2005; Córdoba et al. 2013) are considered overfished in their natural distribution areas. In several places, local management programs are in place and fisheries are under systematic control, as is the case with participatory management of Arapaima fishing in the Mamiruarú Sustainable Development Reserve in Brazil (IDSM 2021) and the Pacaya-Samiria National Reserve in Peru (Kirkland et al. 2020).

Overfishing is no longer restricted to large, highly sought species, it also affects several of the smaller Characiformes species that now dominate fish landings, such as Prochilodus nigricans (Catarino et al. 2014; Bonilla-Castillo et al. 2018) Psectrogaster spp. (Garcia-Vásquez et al. 2015), Triportheus sp., Osteoglossum bicirrhosum, and Mylossoma duriventre (Fabré et al. 2017). This is particularly visible around large cities, such as Manaus and Iquitos, which can cast defaunation shadows of over a thousand kilometers, as evidenced for tambaqui (Tregidgo et al. 2017; Garcia et al. 2009). The progressive replacement in fisheries of large, long-lived species by smaller species with faster turnover is a well-described phenomenon known as “fishing down” (Welcomme 1995, 1999), or “fishing down the food web” when an associated decline in trophic levels is observed in the exploited species (Pauly et al. 1998).

Most commercial and overexploited fish species in the Amazon Basin are migratory, traveling from a few hundred to several thousand kilometers (Barthem and Goulding 2007; Goulding et al. 2019). Migratory species account for over 90% of fisheries landings in the Amazon Basin, generating incomes of over US $400 million (Duponchelle et al. 2021). Although the proportion of migratory species is slightly lower in unmonitored subsistence fisheries, which represent at least as much volume as the landed commercial fisheries (Bayley 1998; Crampton et al. 2004), they still dominate the catches (Batista et al. 1998; Castello et al. 2011; Castello et al. 2013b). Migratory fishes are the species most at risk from the growing anthropogenic activities threatening the Amazon’s aquatic ecosystems (review in Duponchelle et al. 2021).

Fish overharvesting could have indirect negative effects on terrestrial plant biodiversity and conservation because many commercial species have frugivorous diets and play key roles in dispersing seeds (ichthyochory) and in seed germination processes (review in Correa et al. 2015a). This is further aggravated by the fact that larger fish, which are the main targets for fisheries, are also the most effective seed-dispersal agents (Correa et al. 2015a,b; Chapters 3 and 4).

Modern aquaculture could contribute to the conservation of endangered species, which are overharvested. Most of the aquaculture farms around major Amazon cities have only recently begun operation and focus on much-consumed species. Tambaqui is the native fish species most frequently farmed in Brazil (Araújo-Lima and Goulding 1998; de Oliveira and Val 2017). Pirarucu (Arapaima) and some other fish species, such as matrinchà (Brycon amazonicus), are also farmed. The major challenge to fish farming in the Amazon is feeding because local production of fish feed is limited. Other inputs, such as ice and rock salt, can also be difficult to obtain. The improvement of transportation and other conditions would also contribute to the use of by-products (such as leather) from these fish species. Other aquatic groups, such as turtles, are illegally harvested for sale as food (Salisbury 2016). Dolphins are under severe pressure from the practice of killing them to use their flesh as fish bait, especially for the piragatinga or mota catfish (Callophysius macropterus), and caimans are also killed for this purpose (Brum et al. 2015).
20.5.2 Ornamental fish

The aquarium trade is a growing, multi-billion-dollar industry (Andrews 1990; Stevens et al. 2017). Fish are among the most popular pets in the world (Olivier 2001), and the harvesting of wild specimens for the international ornamental trade is a major conservation issue (Andrews 1990; Chao and Prang 1997; Moreau and Coomes 2007). The Amazon Basin accounts for ~10% of the global trade of freshwater ornamental fish, with Brazil, Colombia, and Peru as the major exporters; in 2007, the total declared (greatly underestimated) export value from these three countries was around US $17 million (Monticini 2010). Although artificial breeding could be beneficial for the conservation of aquarium species (King 2019), nearly all specimens exported from South America are taken directly from the wild (Olivier 2001). There is no up-to-date published estimate of the overall number of Amazonian fish species exploited by the ornamental trade, but about 700 species are exported from Brazil (IBAMA 2012), >100 from Colombia (Ortega Lara et al. 2015) and >300 from Peru (Gerstner et al. 2006). These lists share many species, but widespread species may also hold cryptic diversity (e.g., Estivals et al. 2020). These figures are probably underestimates, as many different species can be exported under a single name (Moreau and Coomes 2007). Therefore, a conservative estimate could consider that between 700 and 1,000 species of fish are exploited by the ornamental trade in the Amazon Basin.

One major impact of the ornamental trade is that it favors invasion of exotic species and their associated parasites (Chan et al. 2019; Gippet and Bertelsmeier 2021). The effects of the ornamental trade on natural fish populations in the Amazon, however, remain poorly studied. Anecdotal information suggests population collapses or declines under exploitation pressure at some locations in the Rio Negro for discus (Symphysodon discus) (Crampton 1999) and cardinal tetra (Paracheirodon axelrodi) (Andrews 1990; Chao and Prada-Pedreros 1995). In the Peruvian Amazon, exploitation for the ornamental trade has led to reductions in ornamental species at study locations by over 50% in fish abundance, diversity, and biomass (Gerstner et al. 2006).

The cardinal tetra is the number-one export species in the ornamental fish trade in Brazil, accounting for 68% of the total value of Brazilian ornamental fish exports (Anjos et al. 2018). The cardinal tetra inhabits the middle and upper Rio Negro, and its trade corresponds to 60% of the economy of the municipality of Barcelos. However, fishery data have yet to be collected to better evaluate the effects of this artisanal fishery on fish populations. Based on information from fishers and the data obtained from sampling ornamental fish (fish caught per area sampled), the world economic collapse that began in 2008 directly affected the gross amount of exported ornamental fish (mostly cardinal tetra).

After the 2008 global financial crisis there was a decrease in both the number of people involved in exploiting ornamental fish and in the catch volume. In fact, the decrease in the 2010s, followed by another economic crisis, ended the boom in ornamental fish export from Brazil. Considering by-catch (other species caught together with the target species), ornamental fisheries would not be sustainable without an observatory group comprising the fisher community, dealers, and researchers. The observatory program is viable for the ornamental fish market and can increase sales by emphasizing fish preservation and the well-being of the local communities that are still active in this trade in a manner similar to what occurred with fair-trade coffee (Zehev et al. 2015).

Owing to the increasing exploitation of ornamental fish, the silver arowana (Osteoglossum bicirrhosum) has been placed on the Red Book list in Colombia (Mojica et al. 2012), and this species may also be threatened in Peru (Moreau and Coomes 2006, 2007). Export of this species for ornamental purposes is prohibited in Brazil (Lima and Prang 2008).
20.6 Invasive Species

The introduction of invasive fish species worldwide is responsible for the homogenization of aquatic fauna, driven especially by a few species, such as *O. niloticus*, *C. carpio* and *P. reticulata* (Vil-léger et al. 2011; Toussaint et al. 2016a,b), all of which have been introduced into the Amazon. Invasive species are used for farming, cultivation of ornamental species, and recreational fishing (Lima-Junior et al. 2018). Fish introduced to the lakes and reservoirs of the Brazilian Amazon often belong to predatory species (*Cichla* spp., *Astronotus* spp. and *Pygocentrus nattereri*), contributing to the reduction in abundance or loss of native fish species, with whole-ecosystem consequences such as loss of native species’ habitats, decrease of local species due to the many invasive species that eat native fish species’ eggs, and competition for food, leading to changes in species composition and to modifications of food-webs (Zaret and Payne 1973; Latini and Petriere 2004; Pelicice and Agostinho 2009; Pelicice et al. 2015b; Fragos-Moura et al. 2016). In Andean watercourses in Bolivia and Peru the introduction of the predatory rainbow trout *Oncorhynchus mykiss* resulted in local extirpation or greatly reduced abundance of native *Astroblepus* spp. (Ortega et al. 2007; Van Damme et al. 2011). In the lake Titicaca system, introduced rainbow trout (*Oncorhynchus mykiss*) and pejerrey (*Odontesthes bonariensis*) resulted in the extinction of *Orestias cuvieri* and in declines in many other native species (Andersson and Maldo-nado-Ocampo 2011; Ortega et al. 2007; Van Damme et al. 2009).

Sport fishing and collection for ornamental and aquaculture purposes have motivated the introduction of tilapia (*Oreochromis niloticus*), guppy (*Poecilia reticulata*), and common carp (*Cyprinus carpio*), but their impacts are still poorly investigated (Ortega et al., 2007; Anderson and Maldo-na-Ocampo 2011; Van Damme et al. 2011; Gutiérrez et al. 2012; Doria et al. 2020). In 2020, the Brazilian government authorized and initiated the promotion of raising tilapia in cages in reservoirs (Charvet et al. 2021), despite the fact that tilapia can affect native species through competition and spread of diseases (Deines et al. 2016). If tilapia populations become dense, they can release enough phosphorus into the water to cause eutrophication, which leads to widespread fish mortality, as has already occurred in lakes outside the Amazon (Starling et al. 2002).

The proliferation of hydroelectric dams in the Amazon makes the region more vulnerable to invasive species, as dams facilitate invasive fish species. For example, specialist species adapted to running water progressively disappear from the newly created reservoirs upstream of dams and, if eurytopic native species (species able to tolerate a wide range of ecological conditions) cannot take their place, then the niche is often taken by alien species (Liew et al. 2016). This is facilitated by potential tilapia entry into reservoirs; in addition to the recently legalized rearing of tilapia in cages in reservoirs in Brazil, many aquaculture farms are installed close to reservoirs and fish may escape when water is drained from the ponds.

The introduction of some Amazonian predatory fish species into regions outside their original range can have major effects on local fish communities. This is the case for tucunaré (*Cichla* spp.) and pirarucu or paiche (*Arapaima* spp.) (Miranda-Chumacero et al. 2012). A recent review revealed 1,314 records of non-native fish species (in 9 orders and 17 families), in the Amazon Basin since the first record in 1939, with a sharp increase in the last 20 years (75% of occurrences) (Doria et al. 2021). Non-native species were mainly introduced by the ornamental trade, or for aquaculture and sport-fishing. The most widespread non-native species were *Arapaima gigas* (outside of its native range), *Poecilia reticulata*, and *Oreochromis niloticus*. Overall, our current understanding of impacts of invasive fish species in the Amazon remains limited due to a paucity of studies (Frehse et al. 2016; Doria et al. 2021).
20.7 Deforestation

Deforestation is a driver of aquatic degradation that can have effects that differ between the directly impacted areas and areas downstream; local deforestation can have regional consequences. At the small to medium scale, deforestation usually results in increased runoff and discharge; for example, deforestation resulted in a 25% increase in discharge in large river systems such as the Tocantins and Araguaia Rivers, with little change in precipitation (Coe et al. 2009). At a larger scale, atmospheric feedbacks (reduced precipitation caused by decreased evapotranspiration) can change the water balance, not only in the basins where deforestation has occurred but throughout the entire Amazon via atmospheric circulation (Coe et al. 2009).

By increasing water runoff and sediment loads carried by the rivers, deforestation typically alters geomorphological and biochemical processes downstream with consequences for soil erosion and the biological productivity of aquatic ecosystems (Neill et al. 2001; Coe et al. 2009; Deegan et al. 2011; Iñiguez-Armi jos et al. 2014; Ilha et al. 2018). For example, stronger floods result in the washing out of substrate and associated production of the benthos on which migratory detritivores feed (Flecker 1996). Decreased water transparency reduces algal and zooplankton production in floodplain lakes, which are important feeding and nursery areas for most fish species (Bayley 1995; Pringle et al. 2000).

The chemical properties of streams flowing through pastures are radically different from those of streams in neighboring forests (Krusche et al. 2005; Neill et al. 2006; Deegan et al. 2011). Solutes in groundwater are also affected, thereby contributing to changes in stream chemistry (Williams et al. 1997). Direct exposure to sun and changes in temperature, oxygen, chemical content, and bottom substrates greatly affect aquatic fauna (da-Silva Monteiro Júnior et al. 2013). Increased water temperatures and reduced oxygenation during the dry period can be lethal to fish (Winemiller et al. 1996).

Cardinal tetr as are sensitive to increased temperatures (Fé-Gonçalves et al. 2018). The two congeneric species of cardinal tetr as are distributed in inter-fluvial areas in the upper part of the Rio Negro Basin and inhabit two distinct environments with different vegetation covers and temperatures (Marshall et al. 2011). The water temperatures of these environments differ by less than 2°C but coincide with the maximum thermal limits for both species (Campos et al. 2017). Small characins are usually found in small, forested terra firme (upland) streams. The increase in water temperature caused by deforestation will therefore affect fish species living in streams in deforested areas. Overall, severe disturbances in fish communities can result because many species live in streams with temperatures close to their critical tolerance limits (Campos et al. 2018).

In small streams, deforestation reduces the availability of large instream wood, which plays critical roles in the structure, diversity, and abundance of fish communities, thus impacting fisheries and ecosystem functions (Wright and Flecker 2004). Loss of smaller debris could impact the benthic insects and macroinvertebrates that fish eat. Recent studies have demonstrated negative impacts of deforestation on fishery yield (Castello et al. 2018) and fish species richness, taxonomic diversity, abundance (Lobón-Cerviá et al. 2015; Arantes et al. 2018), biomass, and functional diversity (Arantes et al. 2019a). All these impacts can be reduced if riparian forests are maintained; for example, if an area is converted to pasture but a forested strip is left along the margins of waterbodies, these waterbodies will be less affected (de Paula et al. 2021). The wider the strip, the less the impact on aquatic ecosystems; for example, in the eastern Amazon the percentage of forest cover within 100 m of a stream is closely related to macroinvertebrate diversity in the stream (de Paula et al. 2021). Even a small fraction of forest loss in a catchment is sufficient to transform communities of benthic invertebrates and vertebrates (mainly...
fish) in Amazonian streams (Brito et al. 2020; Campos et al. 2018). Reducing forest cover by only 6.5% within 50 m of a stream is enough to cross thresholds for aquatic invertebrates (Dal'corte et al. 2020). Furthermore, a forest border protects stream banks from erosion, prevents destruction of the stream bed, maintains cooler temperatures, and helps maintain better water quality. In Brazil, the legal requirement for such protection has been greatly reduced since 2012, when the country’s Forest Code was replaced by a law that redefines the water level from which the required forest border is measured, changing the basis for measurement from the maximum to the minimum level of the river. This eliminated almost all requirements for protection along most medium and large Amazonian rivers due to their great annual variation in water level.

20.8 Pollution

20.8.1 Agricultural chemicals

Expansion of chemical-intensive crops such as soybeans and oil palm increases the risk of water contamination from agricultural chemicals. The expansion of soybean production in the southern Amazon is of particular concern due to the heavy use of herbicides, including glyphosate (e.g., Roundup®). There are few direct measurements of Amazonian watercourses. A 2016 review on pesticides in Brazilian freshwaters found no studies in the country’s Amazon biome (Albuquerque et al. 2016). A 2020 study in the area near Santarém, where soybeans are expanding, sampled watercourses and/or groundwater at 28 sites, detecting glyphosate at 11 sites at levels between 1.5 and 9.7 µg/L (Pires et al. 2020). The presence of pesticides in aquatic animals indicates water contamination, as in the case of organochlorine pesticides in fish in the Tapajós River (Mendes et al. 2016), turtles in the Xingu River (Pignati et al. 2018), and Amazon River dolphins in the Solimões (Upper Amazon) and Madeira Rivers (Lailson-Brito Jr. et al. 2008). The same dolphins also had polychlorinated biphenyls in their blubber (Lailson-Brito Jr. et al. 2008; Torres et al. 2009).

In Brazil, several hundred agricultural chemicals have been newly authorized for use under the current administration, many of which are banned in other countries (Ferrante and Fearnside 2019). Pesticides, herbicides, and medicines and other drugs (including endocrine disrupters) are released into the environment. For many compounds, the period of time they remain in the environment is still undetermined. Transition metals and other pollutants in Amazonian aquatic communities may affect local fish species differentially due to their respiration, reproduction, trophic position, and metabolic characteristics, which vary among different fish assemblages (Duarte et al. 2009; Braz-Mota et al. 2017). In Venezuelan streams, for example, particulate or dissolved compounds coming from agricultural effluents resulted in strong water de-oxygenation through micro-organismal decomposition and, subsequently, in the loss of fish species (Winemiller et al. 1996). By killing mostly adult fish, these relatively localized effects have potentially long-term consequences (Braz-Mota et al. 2017). The herbicide glyphosate and the pesticide Malathion have been shown to cause metabolic and cellular damage in fish exposed to concentrations lower than their 50% lethal concentrations (LC₅₀) (Silva et al. 2019; Souza et al. 2020).

Laboratory experiments on fish have shown that glyphosate and other herbicides cause damage to the liver and gills, as well as DNA breakage and increased expression of oncogenes (Braz-Mota et al. 2015; Silva et al. 2019; Souza et al. 2020). Field observations on frogs monitored before and after these herbicides were applied in an area in the central Amazon revealed that two species (Scinax ruber and Rhinella marina) developed malformations that were not present before the herbicide application or at a location 600 m from the application site. In addition, three previously abundant Leptodactylus species became locally extinct (Ferrante and Fearnside 2020).
20.9 Oil spills and toxic waste

The western part of the Amazon Basin has large oil reserves (Chapter 19). Crude oil spills and untreated toxic waste from oil and gas exploitation are notorious in the Amazon portions of Ecuador (Jochnick et al. 1994) and Peru (Kimerling 2006; Orta Martínez et al. 2007; Yusta-García et al. 2017) (Figure 20.8). In the Ecuadorian Amazon between 1972 and 1992, 73 billion liters of crude oil was discharged into the environment, 1.8 times the 41 billion liters released by the Exxon Valdez disaster in Alaska (Sebastián and Hurtig 2004; Kimerling 2006). Over this period, 43 billion liters of produced water (oilfield brine) was also released, which contains salts that disrupt fish migrations (Kimerling 2006).

Oil is toxic to fish (Sadauskas-Henrique et al. 2016), and oil-associated contamination can have far-reaching impacts on Amazonian aquatic communities because the oil can disperse over the entire downstream network (Yusta-García et al. 2017). Oil extraction produces large amounts of toxic mud and produced water, which in Peru and Ecuador have been routinely released into the environment rather than being pumped back into wells (Kimerling 2006, pp. 450-453; Moquet et al. 2014). This brine has both high salt concentrations and a variety of toxic substances (including heavy metals), in addition to significant amounts of oil. Concentrations of hydrocarbon-related toxins have been found in Ecuadorian streams up to 500 times higher than those allowed by regulations in Europe (Sebastián and Hurtig 2004).

Figure 20.8 Oil leaks from a submerged pipeline in Peru. Source: Fraser (2014).
The effects of oil can last for decades, as seen following a spill of 11 billion liters of crude into the Coca and Napo Rivers in Ecuador in 1987; as of 2006, the affected rivers had not recovered their fish biodiversity (Kimerling 2006, p. 458). Oil spills also greatly impact aquatic invertebrate communities, reducing both abundance and species richness, as shown by studies in streams and floodplains affected by oil near Manaus, Brazil (Couceiro et al. 2006, 2007a).

Extraction of oil and natural gas near the Urucu River, in the western part of the Brazilian Amazon, is a concern due to potential impacts on adjacent waterbodies. Although the oil company responsible (Petrobras) ensures that all safety operation protocols are being observed, there is always the possibility of an oil spill. Oil pumped from the Urucu wells travels in large barges down the Solimões (Upper Amazon) River from Coari to Manaus, where it is refined (Figure 20.9).

**Figure 20.9** Transport of oil by pipeline from Urucu (RUC) to Coari and then by barge from Coari to Manaus. The inset map shows oil project areas throughout the Amazon.
Amazon fishes have evolved in hypoxic water and have developed many strategies to either breathe air or take water from the film at the top of the water column, which is richer in oxygen (Val et al. 1998; Soares et al. 2006). As mentioned above, these strategies threaten air-breathing fish if oil spills occur (Val and Almeida-Val 1999).

Brazil’s proposal for the Solimões Sedimentary Basin oil and gas project is rapidly moving forward and will open a vast “strategic influence area” covering 47 million hectares (larger than the US state of California) to exploitation in the western Brazilian Amazon (Fearnside 2020b) (Figure 20.10). Within this area, wells would be located at the most-promising locations (green lines in Figure 20.10) where seismic surveys have already been completed. Rights to the first drilling blocks have already been sold to Rosneft, a Russian company that Greenpeace-Russia accuses of causing over 10,000 oil spills throughout the world (Fearnside 2020c). This oil and gas project also carries a substantial risk of improving road access to the vast “trans-Purus” region between the Purus River and Brazil’s border with Peru, resulting in deforestation of the last great block of intact forest in the Brazilian Amazon (Fearnside et al. 2020; see also the views of Brazil’s Ministry of Mines and Energy in Brazil EPE 2020a,b; Fearnside 2020b,c; Vieira 2020a,b).

20.10 Mining

Gold mining, much of which is illegal, is widespread in the Amazon Basin (Figure 20.11). In Brazil it occurs in rivers such as the Tapajós,
Tocantins, Madeira, Xingu, Negro, Amapari, and Solimões or Upper Amazon (Figure 20.12; Roulet et al. 1999; dos Santos et al. 2000); in Bolivia in the Madeira, Beni, and Iténez Rivers (Pouilly et al. 2013); in Colombia in the Putumayo, Caquetá, Guanía, Vaupés, and Inirida Rivers (Nuñez-Avellaneda et al. 2014); in Ecuador in the Nambija River, and in French Guiana along the tributaries of the Black River (Barbosa and Dorea 1998). Illegal invasion of Indigenous areas in Brazil by gold miners (garimpeiros) has long been a major impact on these areas (Figure 20.13), including their aquatic ecosystems. A bill that would legalize these and other activities in Indigenous areas has the potential to greatly increase these impacts (Branford and Torres 2019; Villén-Pérez et al. 2020; Ferrante and Fearnside 2021). It is estimated that more than 200,000 tons of mercury have been shed by gold mining in the Brazilian Amazon since the late 19th Century (Bahía-Oliveira et al. 2004).

Gold mining is estimated to account for 64% of the mercury entering Amazonian aquatic systems (Roulet et al. 1999, 2000; Artaxo et al. 2000; Guimaraes et al. 2000). The remaining amount comes from runoff from natural deposits that are eroded by deforestation (33%) and atmospheric emissions resulting from deforestation and forest fires (3%) (Roulet et al. 1999; Souza-Araújo et al. 2016). On the basin scale, the dynamics of mercury involve abiotic physical processes (i.e., downstream transport of sediments). Elemental mercury can then be turned into toxic methylmercury by specific bacteria in anoxic environments, such as those created at the bottom of reservoirs (Section 20.2.1.4) or in thermally stratified natural lakes and rivers.

Methylmercury enters aquatic food webs and bio-accumulates in successively higher trophic levels (Morel et al. 1998; Ullrich et al. 2001). Vertebrate populations that have accumulated mercury migrate upstream, including both fish migrations for spawning and side migrations in the floodplains (Molina et al. 2010; Nuñez-Avellaneda et al. 2014; Mosquera-Guerra et al. 2019). High concentrations of total mercury (Hg) and methylmercury (MeHg) in aquatic trophic networks have been documented since the 1980s (Martinelli et al. 1988; Lacerda 1997; Lacerda and Salomons 1998). soil independent of human activities; since Amazonian soils are ancient, they have slowly accumulated mercury that is injected into the atmosphere by volcanic eruptions and deposited by precipitation worldwide. Fish consumption by the Amazon’s human communities causes some of the world’s highest recorded mercury levels in human hair, along with associated health issues (Passos and Mergl 2008). Through fish consumption, humans also bioaccumulate mercury (Chapter 21).

Among endangered species, high concentrations of mercury have been reported in the giant otter (Pteronura brasilienensis) in Brazil (Dias Fonseca et al. 2005); in the Amazon River dolphin (Inia geoffrensis) in Colombia, Brazil, and Bolivia (Rosas and Leith 1996; Mosquera-Guerra et al. 2015, 2019); and in the gray river dolphin (Sotalia fluviatilis) in Brazil (Mosquera-Guerra et al. 2019). Along the coast of the Amazon, mercury was also found in tissues of the coastal dolphin (S. guianensis) (de Moura et al. 2012). Effects of mercury on small cetaceans include liver abnormalities and serious disorders in the kidney and brain (Augier et al. 1993). Elsewhere, the combination of mercury with other pollutants in small cetaceans resulted in sensory deficits, behavioral deficiency, anorexia, lethargy, reproductive disorders and death of fetuses, as well as deficiencies in the immune system that facilitate the appearance of pneumonia and other infectious diseases (Cardellicchio et al. 2002). It remains unknown whether the same impacts are occurring in Amazon River dolphins and marine dolphins.

Preparations for large-scale industrial mining operations are rapidly moving forward (Arsenault 2021). The Canadian mining company Belo-Sun is preparing a massive operation just downstream of the Pimental Dam (part of the Belo Monte complex on the Xingu River). The operation would extract...
Figure 20.11. Official mining concessions and illegal activities.
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Figure 20.12 Sediment from gold mining enters the Tapajos River at its confluence with the Crepuri, one of several tributaries in central Pará discharging sediments from gold mining into the Tapajós. Source: Guimarães (2020). Photograph: Jean R.D. Guimarães.

Figure 20.13 Mining in Yanomami Indigenous Territory in 2020. Source: Chico Batata - Greenpeace.
gold from two open-pit mines beside the Volta Grande (Big Bend) stretch of the river that is already heavily impacted by reduced water flow due to the Belo Monte complex. Risks include tailings dams, cyanide use, and demand for large amounts of water from the already insufficient flow of the Volta Grande (Emerman 2020). The 44 m high tailings dam will remain indefinitely, although the mine is estimated to be exhausted after 17 years of operation. Were the tailings dam to rupture, it could provoke a catastrophe equal to the 2015 Mariana disaster on the Rio Doce in Minas Gerais (Tófoli et al. 2017), and release over 35 million m$^3$ of tailings containing cyanide (Emerman 2020).

Bauxite mining and the processing of ore to produce alumina and then aluminum can release fine toxic particles known as “red mud” into aquatic ecosystems. At the Mineração Rio do Norte bauxite mine on the Trombetas River in Pará, a large lake (the Lago Batata) was completely filled with 24 million tons of this mud in the 1980s, killing virtually all aquatic life (Soares 2015; Borges and Branford 2020). In 2018, a holding pond for red mud burst at the Norsk Hydro alumina plant in Barcarena, Pará (Fearnside 2019). Water was contaminated as far away as Abaetetuba, 48 km from the alumina plant (Barbosa 2018).

20.11 Urban sewage and plastic waste

Urban sewage greatly affects aquatic invertebrates, reducing both abundance and species richness, as shown by a series of studies in 20 streams in the Manaus area (Couceiro et al. 2006, 2007a,b, 2011; Martins et al. 2017). The effect varies by taxonomic group, which allowed an index of pollution severity to be developed using aquatic insects as bioindicators (Couceiro et al. 2012). Streams in Manaus are also contaminated with a variety of hydrocarbons both from biomass burning and petroleum (de Melo et al. 2020). Streams in Manaus have been found to contain human pharmaceuticals, as well as traces of cocaine, but these are diluted below detection limits after entering the major rivers (Thomas et al. 2014; de Melo et al. 2019). Pollution with pharmaceutical compounds can affect fish (dos Santos et al. 2020) and macrophytes (Otomo et al. 2021). Pharmaceutical pollution is a growing threat to aquatic environments throughout Latin America, including Amazonian countries (Valdez-Carrillo et al. 2020). Samples taken at 40 sites along the Amazon River and major tributaries in Brazil found 30-40 compounds near major cities and 1-7 compounds in the Amazon River far from cities (Fabregat-Safont et al. 2021). A different survey at 40 sampling sites along the Amazon River, three tributaries (Negro, Tapajós and Tocantins Rivers),
and four cities found that chemical pollution can cause long-term effects in 50–80% of aquatic species near urban areas (Rico et al. 2021).

Large amounts of plastic are discarded in Amazonian rivers and streams (Figure 20.15), and the presence of microplastics has now been detected in river sediments (Gerolin et al. 2020), in the sand of a beach on the coast of the Amazon region, and in a river beach in the Ecuadorian Amazon (Lucas-Solis et al. 2021; Martinelli Filho and Monteiro 2019). Microplastics have also been found in fish species from all trophic levels, including 13 species from the Xingu River (Andrade et al. 2019) and 14 from the Amazon estuary (Pegado et al. 2018). Micro- and nanoplastics have impacts on aquatic ecosystems, including serving as carriers for persistent organic pollutants (POPs) (Besseling et al. 2019) and transferring chemicals that can provoke hepatic stress in fish (Rochman et al. 2013). They can also affect mammals (Rubio et al. 2020).

Many cities, towns, and municipalities across the basin do not have plastic and waste management in place, and this remains as an important challenge to be tackled by policy makers for the conservation of healthy freshwater ecosystems in the region. The Amazon River is estimated to discharge 32,000-64,000 tons of plastic into the Atlantic Ocean annually (Lebreton et al. 2017). The Amazon River has also been identified as a major source of organic plastic additives in the water of the tropical North Atlantic (Schmidt et al. 2019).

20.12 Interactions among drivers

Although most drivers of degradation in aquatic ecosystems have been discussed separately, several are highly correlated, often interacting, and aquatic organisms will have to cope with some combination of these drivers. The impacts of land-cover change, global climate change, dams, and mining have interactions that are causing large-scale degradation of the Amazon’s freshwater
ecosystems, and current development trends imply dramatic increases in these impacts (Castello and Macedo 2016).

Several of the drivers discussed here can directly or indirectly promote deforestation. Hydropower dams induce road construction, which in turn lead to increased deforestation and agriculture, which often also result in more deforestation (Finer and Jenkins 2012; Chen et al. 2015; Lees et al. 2016; Forsberg et al. 2017; Anderson et al. 2018). As already explained, regulation of hydrological cycles by dams will isolate large portions of floodplains, which will likely be exploited for agriculture, further increasing deforestation (Forsberg et al. 2017).

Similarly, the planned waterway in the Tapajós sub-basin is likely to encourage further deforestation directly through increased soy production in Mato Grosso. Soy plantations cause aquatic ecosystems to receive runoff containing fertilizers, herbicides, pesticides, and sediment from soil erosion (Section 20.6.1). Waterways also reduce transportation costs and induce replacement of pasture by soy, resulting in indirect land-use change, where cattle ranchers sell their land to soy farmers and move to other parts of the Amazon, clearing forest for cattle pasture (Arima et al. 2011; Fearnside 2015c) (see Chapters 14 and 15).

One impact of waterways is that they serve to justify hydroelectric dams regardless of how severe the impacts may be. Without a complete sequence of dams on a river, the entire waterway would cease to function because barges cannot pass rapids and waterfalls, which are eliminated by reservoirs. The Tocantins/Araguaia waterway (Fearnside 2002b) and the Tapajós waterway (Fearnside 2015c) both serve as examples. In the case of the Madeira River, a plan for 4,000 km of waterways in the Amazon portion of Bolivia, intended to transport soybeans, was used as an argument in the viability study for Brazil’s Santo Antônio and Jirau Dams (Fearnside 2014a,b).

Exploitation of new sources of energy, such as oil, usually require road construction, hence deforestation (Anderson et al. 2018; Fearnside 2020b). Oil exploitation also has strong combined effects with dams, devastating aquatic biota where these drivers intersect (Anderson et al. 2019). Indirect effects of oil exploitation, such as road building and consequent deforestation, can lead to fragmentation of aquatic connectivity or habitat loss for migratory species, further aggravating the effects of dams and waterways. In the Peruvian Amazon, the Interocceanic Highway has had a dual impact on the rivers and associated terrestrial ecosystems. As shown by satellite imagery, this road promoted land-use change due to agricultural expansion in the north, while at the same time facilitating access to previously pristine forests along the Malinowsky and Inambari Rivers for the extraction of alluvial gold (Finer et al. 2018; Sánchez-Cuervo et al. 2020).

Climate-induced increases in the severity of droughts and lengthening dry seasons will lead to further deforestation and fires (Malhi et al. 2009). The effects of climate change will also interact with other anthropogenic impacts. Warming trends will increase water temperatures, increasing the toxicity of pollutants to organisms and bioaccumulation of mercury in aquatic food webs (Ficke et al. 2007; Val 2019). The expected trend of declining discharges in the Amazon Basin, except in the western part (Sorribas et al. 2016; Farinosi et al. 2019), could result in fish biodiversity loss of up to 12% in the Amazon Basin and 23% in the Tocantins Basin (Xenopoulos et al. 2005). Droughts and decreased river discharge are also expected to impact fish community composition, population size and structure, reproduction, and recruitment (Poff et al. 2001; Lake 2003; Freitas et al. 2013; Frederico et al. 2016).

Increased temperatures and reduced oxygen concentrations resulting from reduced water volumes are expected to be detrimental for many aquatic organisms, including fish (Lake 2003; Ficke et al. 2007; Frederico et al. 2016; Nelson and Val 2016; Gonçalves et al. 2018; Lapointe et al.
2018; Campos et al. 2019). In adult organisms, energy is allocated to growth, reproduction, and maintenance metabolism (Val and Almeida-Val 1995; Almeida-Val et al. 2006; Wootton 1998). The surplus energy spent in compensating for increased thermal conditions will therefore come at the expense of growth and reproduction, and it is likely to increase susceptibility to disease (Ficke et al. 2007; Freitas et al. 2012; Oliveira and Val 2017; Costa and Val 2020). Higher temperatures are also expected to favor eutrophic conditions and to stimulate macrophyte development in floodplain lakes, modifying food-web dynamics and affecting the fish that depend on them (Ficke et al. 2007).

Global warming and reduced oxygen availability result in shrinking body size in many organisms (Sheridan and Bickford 2011), and this is also expected in fishes (Cheung et al. 2013; Oliveira and Val 2017; Pauly and Cheung 2018; Almeida-Silva et al. 2020), which could impact fisheries across the region. Declining body sizes under global warming could lead to ecosystem alteration through a trophic cascade for predatory species (Estes et al. 2011), or through disruption of carbon flows for detritivorous species (Taylor et al. 2006) and consequent decreased recruitment because reproductive output is proportional to body size in most fishes. Expected climate-driven reductions of fish size will also further accelerate the fishing-induced size decreases that have already been observed for commercial species.

Fragmentation of river networks by hydroelectric dams and other infrastructure will constrain potential range shifts of aquatic species to cope with expected temperature rise under climate change (Myers et al. 2017). Range shifts of fish to higher altitudes as a result of climate change have already been documented, and river fragmentation by dams will block this form of adaptation (Herrera-R 2020). Andean aquatic species will likely be particularly impacted because most dams have been built or are planned on Andean tributaries (Forsberg et al. 2017; Anderson et al. 2018; Tognelli et al. 2019).

20.12 Conclusions

Rivers provide connections between widely separated aquatic and terrestrial ecosystems through flows of water, sediment, and nutrients, and through fish migrations. Fragmenting rivers therefore has consequences that are far-reaching (and often international).

Clean, free-flowing rivers and their interacting floodplain ecosystems generate ecosystem services that are important at local, regional, and global scales (e.g., fisheries for food security, sediment transport, and carbon sequestration).

Aquatic ecosystems are particularly prone to cumulative or synergistic impacts. These include the effects of multiple dams on rivers and the combined impacts of changes in river flows, oxygen levels, water temperatures, and levels of pollution.

20.13 Recommendations

- Dams with installed capacity ≥10 MW should not be built in the Amazon. Dams with installed capacity <10 MW which would power a single town or village can be built with the proper environmental licensing and using a risk-based approach. Rather than building Amazonian dams, energy policy should prioritize electricity conservation, halt exports of energy-intensive products, and redirect investment in new electricity generation to wind and solar sources.

- Dams with installed capacity <10 MW have significant impacts and should not be built to feed national or regional grids. The severe cumulative effect of blocking multiple tributaries with these dams should also be considered.

- Decision making processes on infrastructure projects should be reformed such that direct and indirect environmental and social impacts are compiled and democratically debated before decisions are made.

- Selected watersheds throughout the Amazon need to be preserved for research, long-term monitoring, and protection of genetic and species diversity. These watersheds will also
maintain ecological communities that can be needed for recovery efforts.

- Rivers and streams should be protected by an adequate forest border when surrounding land is converted to other uses.
- Better regulation and monitoring of exotic species is needed, especially for fish culture. Interbasin water diversion projects, which inevitably lead to introduction of exotic species, should be avoided.
- Adequate controls are needed on urban sewage, plastic pollution, mercury and other heavy metals, and on the use of agro-chemicals.
- Control of sediments and waste from mining is needed.
- Alluvial mining must be banned across the Amazon Basin to preserve aquatic biodiversity, floodplain forests, and human health.
- Regional governments and municipalities must prioritize the cleaning of sewage water in order to preserve the health of aquatic biota and human populations.
- Because aquatic resources are not private property, they require cooperative arrangements to manage their use (including the exclusion of outside fishing vessels) and enforcement of restrictions on overharvesting.
- Proper accounting of the greenhouse-gas emissions of Amazonian dams is needed.

20.14 References


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