Chapter 20
Drivers and impacts of changes in aquatic ecosystems
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Science Panel for the Amazon
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 Amazon 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, industrial and sewage waste contaminate Amazon 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 the agriculture that replaces forest 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.
- Biological productivity of aquatic ecosystems is affected both downstream and upstream of these impacts.

Abstract

Amazon aquatic ecosystems are being destroyed and the threats to their integrity are projected to grow in number and intensity. In this chapter we review a number of these threats. Hydroelectric dams (n=307 existing or under construction) have changed almost every aspect of Amazon aquatic ecosystems, and many more dams are planned (n=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, 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

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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 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 Amazon forest. Pollution sources include toxins from agriculture and industrial and urban waste, such as plastic, mercury, transition metals like Cu, Cd, Pb, Ni, etc., 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 the rivers converted to this use, particularly affecting the reproduction habitats of freshwater species. Climate change impacts aquatic ecosystems through increased temperature and through 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 \( \geq 10 \) MW should be built in Amazonia, 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

Amazonia’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 usual focus 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 Amazonia reflects 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 are to be described such that the actual number is likely to be above 3000 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.

Amazon 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 estuary. Likewise, a dam blocking migratory species causes upstream effects reaching all the way to the Amazon 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 of commercial and ornamental species) can disrupt aquatic food webs; introduction of invasive species can disturb native species communities, causing loss of habitats to the native species, 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 & 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 (Fearnside 2014; 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 Amazonia’s enormous aquatic biodiversity, as well as the health and the well-being of many Amazon residents who depend on fisheries and other aquatic resources for their livelihoods (see Chapter 21).

Aquatic systems in Amazonia 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 those with 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. 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 & Almeida-Val, 1995; Zuanon et al., 2005).

The 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 to cope with environmental hypoxia, fish in the Amazon have developed adaptations to exploit the water-air interface that, in the case of an oil spill, plays against the animals by increasing their contact with the pollutants concentrated at the
top of the water column (Val and Val 1999; Dos Anjos et al. 2011; Souza et al., 2020).

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 nine countries comprising the Amazon Basin. The 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 it was 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
Figure 20.2 Existing and planned hydroelectric dams and waterways in Amazonia. Currently there are 307 dams existing or under construction; and 239 planned or projected (total = 546).
Brazilian Amazonia. The definition of “small” dams varies widely among countries, with 10 MW being “increasingly recognized as the international standard” (Couto and Olden 2018). Brazil’s relaxing its definition to include dams up to 50 MW represents a significant setback in environmental control.

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 Petrere 1988; Ribeiro et al. 1995; Santos et al. 2018). The conversion of a stretch of river from a running water (lotic) to a still water (lentic) one 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.) are among those that have not been able to use the passages in the large Santo Antônio and Jirau Dams, although they are physically able to climb the passages if placed inside them (Figure 20.4). 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). Amazon dams and their ineffective fish passages have already seriously disrupted the migration routes of many fish species, resulted 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 Amazonia 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 Coaracy Nunes Dam on the Araguaí 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 (Chapter 13).”

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 & 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).

Figure 20.3 The various species of “giant catfish” in the Madeira River are already heavily impacted by the Santo Antônio and Jirau Dams that have blocked their annual spawning migration since 2011. Source: Kileen (2007). Photograph: Russell Mittermeier
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 Amazonia’s largest turtle-breeding beaches, the “tabuleiro do Jacare” (e.g., Forero-Medina et al., 2021; 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 have their habitats reduced by the creation of reservoirs and thus decrease in abundance; while others that breed in the standing water of a reservoir, such as mosquitoes, 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 (Tavares de Lima et al. 2000) providing breeding sites for mosquitoes 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 mosquitoes (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 mosquitoes exploded dramatically and Anopheles mosquitoes, which were already abundant before construction of the dam, are also believed to have increased (Fearnside 2005). (See Chapter 21 on health).

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 CO$_2$ until oxygen is no longer available, after which decomposition must end in methane (CH$_4$). 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 CO$_2$ and methane (CH$_4$). One ton of methane has an impact on blocking the passage of infrared radiation that is 120 times that of a ton of CO$_2$ 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 pre-industrial mean), then the impact of CH$_4$ 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, 2017). The impacts of different greenhouse gases are expressed in terms of CO₂ equivalents based on global-warming potentials (GWPs), which represent the effect on global temperature over given time horizon from emitting one ton of the gas relative to the simultaneous emission of one ton of CO₂. Considering the 20-year GWPs from the IPCC's 5th Assessment Report, 25% of the lowland dams would emit even more CO₂ 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 Amazon dams if emissions from the water passing through the turbines and spillways were included in these calculations. Box 1 explains the contribution of Amazon dams to greenhouse-gas emissions.

Considerable uncertainty exists in calculating greenhouse-gas emissions (i.e., CO₂, CH₄ and N₂O) from dams on the scale of Amazonia 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 the 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 (elevation < 500 m above mean sea level) 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, (see 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 Amazon dam (Delmas et al. 2001; Abril et al. 2005). In Balbina, which has a large reservoir and little water flow, the surface emissions are slightly larger than the downstream emission, whereas in Tucuruí, which has approximately the same reservoir area as Balbina but much more water flow, the downstream emission predominates (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 the 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 the reservoirs (Fearnside 2013c). Downstream of the dam the 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 (in Rondônia) 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 at the base of the food chain that supports most of the fish species in 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 along the entire length of the Madeira and Amazon Rivers (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 Tucurui Dam (Odinetz Collart 1987), an impact from which these populations have never recovered (Cintra 2009).

Reducing sediment flows also impact 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 whitewater rivers. In some cases, the process of dam construction can have the opposite effect of temporarily increasing sediment loads in clearwater and blackwater 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. 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 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 being 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

20.2.2 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

**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.
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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 São 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 (igapó) 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).

20.3 Roads

Amazon 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 (hidrovias) (Figure 20.6) 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 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, specific 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 ~2700-km Hidrovía Amazónica (Anderson et al. 2018; Bodmer et al. 2018). Recent field data on fluvial sediment movements and fish biodiversity in the Marañón and Ucayali Rivers in the Peruvian Amazon suggest that the Hidrovía Amazónica project could significantly alter river-channel morphology and consequently impact the 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 transported 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.

River diversion, which is a response to increasing demand for freshwater, causes multiple environmental impacts. The exchange of aquatic organisms native to different catchments can lead to biotic homogenization, constituting the greatest threat of river diversion to Amazon aquatic systems. This is likely to be the result of a planned connection of the Araguaia/Tocantins river system in Amazonia to the São Francisco river system in Northeastern Brazil (Daga et al. 2020).

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, see also Chapter 15). Most large, high-valued fish species, such as the giant pirarucu 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 of participative management of *Arapaima* fishing in the Mamirarú 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. (García-Vásquez et al. 2015), *Triportheus* sp, *Osteoglossum bicirrhosum*, *Mylossoma duriventre*, among others (Fabré et al. 2017). This is particularly visible around large Amazon 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 USD 400 million (Duponchelle et al. 2021). Although the proportion of migratory species is slightly lower in the 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 Amazon 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; see also 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 matrinchã (*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 mata catfish (*Callophysius macropeterus*), and caimans are also killed for this purpose (Brum et al. 2015).

### 20.5.2 Ornamental fish

The aquarium fish trade is a growing, multi-billion US dollar, industry (Andrews 1990; Stevens *et al.* 2017). Fish are one of the most popular animal 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 ~ USD 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 directly extracted from the wild (Olivier 2001). There is no up-to-date published estimate of the overall number of Amazon fish species exploited by the ornamental trade, but ~ 700 species are exported from Brazil (IBAMA, 2012), > 100 from Colombia (Ortega Lara *et al.* 2015) and > 300 from Peru (Gerstner *et al.* 2006). Of course, these lists share many species, but widespread species may also hold cryptic diversity (e.g., Estivals *et al.* 2020). These figures are probably underestimated given that many different species can be exported under a single name (Moreau and Coomes 2007). Therefore, a conservative estimate could consider that between 700 and 1000 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 basin, 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 combining 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 the “fair-trade coffee market” (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* (Villéger et al., 2011; Toussaint et al., 2016a,b) – all of which have been introduced into Amazonia. Invasive species are used in Amazonia for farming, cultivation of ornamental species, and recreational fishing (Lima-Junior et al., 2018). Fish introduced in 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 & Payne, 1973; Latini & Petrere, 2004; Pelicice & Agostinho, 2009; Pelicice et al., 2015b; Fragoso-Moura et al., 2016). In Andean water-courses 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 Titikaka system, the introduced rainbow trout (*Oncorhynchus mykiss*) and pejerrey (*Odonthestes bonariensis*) resulted in the extinction of *Orestias cuvieri* and in declines in many other native species (Anderson & Maldonado-Ocampo, 2011; Ortega et al., 2007; Van Damme et al., 2009). The outcomes of these invasions are unknown: some introduced species may succeed permanently and become adapted, pushing other species to population decreases or even extinction. The rapid adaptation and increase and domination of populations of invasive species has often been explained in conservation studies as resulting from the absence of a predator or the absence of a food competitor (Allendorf et al., 2012; Frankham et al., 2010).

Sport fishing and collection for ornamental and aquaculture purposes have motivated the introduction of tilapia (*Oreochromis niloticus*), guppy (*Poecilia reticulate*), and common carp (*Cyprinus carpio*), but their impacts are still poorly investigated (Ortega et al., 2007; Anderson & Maldonado-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 (*Oreochromis spp.*) 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 occurred in the case of the Paranoá Lake in Brasilia (Starling et al., 2002).
The proliferation of hydroelectric dams in Amazonia makes the region more vulnerable to invasive species, as dams facilitate invasive fish species. For example, specialist species that are 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 the potential sources of tilapia entry into reservoirs: in addition to the recently legalized rearing of tilapia in cages in the reservoirs themselves in Brazil, many tilapia aquaculture farms are installed close to reservoirs and fish may escape through water drained from the ponds.

The introduction of some Amazonian predatory fish species in regions outside their original area of occurrence 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), which were introduced in small dams in northeastern Brazil (Pelicice & Agostinho, 2009). A recent review revealed 1314 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 purposes. 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 Amazonia 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 has 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 the 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 for the biological productivity of aquatic ecosystems (Neill et al., 2001; Coe et al., 2009; Deegan et al., 2011; Iniguez-Armijos 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 tetras are sensitive to increased temperatures (Fé-Gonçalves et al., 2018). The two congeneric species of cardinal tetras 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. 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 & Flecker, 2004). Loss of smaller debris could impact benthic insects and macroinvertebrates that the fish eat. Recent studies have demonstrated negative impacts of deforestation on fishery yield (Castello et al., 2018) and on fish species richness, 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 forest strip is left along the margins of waterbodies, these waterbodies will be less affected by the impacts of deforestation (de Paula et al., 2021). The wider the strip, the less the impact on the aquatic ecosystems; for example, in eastern Amazonia 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 the communities of benthic invertebrates and vertebrates (mainly fish) in Amazon 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 (Dala’corte et al., 2020).

A forest border protects the stream banks from erosion and avoids destruction of the stream bed, maintains cooler temperature 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 this basis for measurement from the maximum to the minimum level eliminated almost all requirement 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

The 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 southern Amazonia is of particular concern due to the heavy use of herbicides, including glyphosate (Roundup ©). Little information is available from direct measurements in Amazon 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, out of which glyphosate was detected at 11 sites at levels between 1.5 and 9.7 µg/L (Pires et al., 2020). 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 in 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 & Fearnside, 2019). Pesticides, herbicides, 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 differ 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 (Roundup®) 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, 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 central Amazonia 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 & Fearnside, 2020).

### 20.9 Oil spills and toxic waste

The western part of the Amazon basin has large oil reserves (see Chapter 19). Crude oil spills and untreated toxic wastes resulting 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 Ecuadorian Amazonia between 1972 and 1992, crude oil discharged into the environment totaled 73 billion liters, or 1.8 times the 41 billion liters released by the Exxon Valdez oil tanker disaster in Alaska (Sebastián & Hurtig, 2004; Kimerling, 2006, p. 458). Over this period 43 billion liters of produced water (oilfield brine) was also released, which contains salts that disrupt fish migrations (Kimerling, 2006, pp. 450-453). Oil is toxic to fish (Sadauskas-Henrique et al., 2016), and oil-associated contamination can have far-reaching impacts on Amazon 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 the 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 & Hurtig, 2004).

The effect of oil can last for decades, as indicated by a spill of 11 billion liters of crude into the Coca and Napo Rivers in Ecuador in 1987, where the affected rivers had not recovered their fish biodiversity by 2006 (Kimerling, 2006, p. 458). Oil spills...
Figure 20.9 Transport of oil from Urucu to Manaus by an oil and gas pipeline from Urucu (RUC) to Coari and by barge from Coari to Manaus. The inset map shows oil project areas throughout Amazonia.
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. The 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). Amazon fishes have evolved in hypoxic water and have developed many strategies that forced them 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 & Almeida-Val, 1999).

Brazil’s proposal for the “Solimões Sedimentary Basin” oil and gas project is rapidly moving forward to 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 along the green lines (see Figure 20.10), which indicate transects where seismic surveys have already been completed. Rights to the first drilling blocks have already been sold to Rosneft, the Russian company that

![Figure 20.10](image_url) **Figure 20.10** Brazil’s proposed “Solimões Sedimentary Basin” oil and gas project. The purple areas are the Urucu “production field” where wells are currently in production. The thin green lines represent the locations for future drilling where seismic surveys have already been carried out. The proposed project’s “Strategic Influence Area,” delimited by the red line, covers 47 million hectares (larger than the US state of California). Source: Brazil, EPE (2020a, p. 65).
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 resulting in 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 Brazilian Amazonia (Fearnside et al., 2020; see also the contested views of Brazil’s Ministry of Mines and Energy on this risk: Brazil, EPE, 2020a,b; Fearnside, 2020b-f; Vieira, 2020a,b).

20.10 Mining

Gold mining is especially prominent in Brazil and Peru, and the scale and consequent impacts of this activity could increase substantially. In Brazilian Amazonia most of the many requests for permits for mineral prospecting are for gold (Figure 20.11). Mining alluvial gold, as by “wildcat” miners (garimpeiros), releases large amounts of sediment into the watercourses (Figure 20.12).

Gold mining, much of which is illegal, is widespread in the Amazon basin (Figure 20.13). In Brazil it occurs in rivers such as the Tapajós, Tocantins, Madeira, Xingu, Negro, Amapari and Solimões or Upper Amazon (Roulet et al., 1999; dos Santos et al., 2000); in Bolivia it occurs in the Madeira, Beni and Iténez Rivers (Pouilly et al., 2013); in Colombia it occurs in the Putumayo, Caquetá, Guáiana, Vaupés and Inirida Rivers (Nuñez-Avellaneda et al., 2014); in Ecuador it occurs in the Nambija River, and in French Guiana it occurs along the tributaries of the Black River (Barbosa & Dorea, 1998). Illegal invasion of Indigenous areas along the tributaries of the Black River (Barbosa & Dorea, 1998). Illegal invasion of Indigenous areas in Brazil by “wildcat” gold miners (garimpeiros) has long been a major impact on these areas, including their aquatic ecosystems, and a bill that would legalize these and other activities in Indigenous areas has the potential to greatly increase these impacts (Branford & Torres, 2019; Villén-Pérez et al., 2020; Ferrante & Fearnside, 2021). It is estimated that the mercury shed by gold mining in the Brazilian Amazon totals more than 200,000 tons since the late 19th Century (Bahía-Oliveira et al., 2004). Gold mining has been estimated to account for 64% of the mercury entering Amazon aquatic systems (Roulet et al., 1999, 2000; Artaxo et al., 2000; Guimaraes et al., 2000). The remaining amount reaches aquatic systems due to runoff from natural deposits that are eroded by deforestation (33%) and by 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 the toxic methylmercury form by specific bacteria in anoxic environments, such as those created at the bottom of reservoirs (Section 2.1.4 in the present chapter) or in thermally stratified natural lakes and rivers.

Methylmercury enters aquatic food webs and bioaccumulates 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 et al., 1997; Lacerda & Salomons, 1998).

Wildlife (mainly omnivorous and carnivorous species) is exposed to MeHg through their diet (Ullrich et al., 2001; Sarica et al., 2005; de Moura et al., 2012). Mercury bioaccumulation causes concentrations to increase greatly in top predators such as large catfish, black caiman, and mammals such as otters, and dolphins (Markert, 2007; Molina et al., 2010; Bossart, 2011; Salinas et al., 2013; Nuñez-Avellaneda et al., 2014; Mosquera-Guerra et al., 2015, 2019). Because many aquatic mammals are at the top of food chains, they are especially threatened by bioaccumulation of mercury (Brum et al., 2021) (Figure 20.14).
Figure 20.11 Official mining concessions and illegal activities
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 20.14 Bioaccumulation of mercury in the Rio Negro (Redrawn from: Kasper, 2018)
In contrast to other sources of contamination, mercury has received considerable attention in the Amazon basin, and several studies have reported mercury concentrations in fish well above the acceptable limit defined by the World Health Organization (0.5 mg kg\(^{-1}\)) (e.g., Hacon et al., 2008; Roach et al., 2013). Nuñez-Avellaneda et al. (2014) evaluated the presence of total mercury in muscle tissue samples of eleven fish species at four locations in the Colombian Amazon, reporting values that ranged between 0.0116 and 2.0123, mean = 0.3549 mg Hg kg\(^{-1}\). Mosquera-Guerra et al. (2015) reported that 54% (n = 103) of the total tissue samples of the catfish species *Calophysus macropterus* (omnivore) from the Amazon had concentrations between 0.11 and 1.66 mg Hg kg\(^{-1}\), coinciding with the findings of Salinas et al. (2013) for the same catfish species. However, elevated levels of mercury in fish can also occur naturally at locations far from human activities (Marshall et al., 2016). This is because mercury is present in the soil independent of human activities – since Amazon soils are ancient, they have slowly accumulated mercury that is injected into the atmosphere by volcanic eruptions and deposited by precipitation worldwide. Dietary fish consumption in Amazonian human communities is responsible for some of the world’s highest recorded mercury levels in human hair, along with associated health issues (Passos & Mergler, 2008). Through fish consumption, humans also bioaccumulate mercury – this is discussed in Chapter 21.

Among endangered species, high concentrations of mercury have been reported in the giant otter (*Pteronura brasiliensis*) in Brazil (Dias Fonseca et al., 2005), in the Amazon River dolphin (*Inia geoffrensis*) in Colombia, Brazil, and Bolivia (Rosas & Lethi, 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 off 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 in 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 planned just downstream of the Pimental Dam (part of the Belo Monte complex on the Xingu River). The operation would extract 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 the tailings dam, cyanide use, and demand for large amounts water from the already insufficient flow of the *Volta Grande* (Emerman, 2020). The 44-m high tailings dam will remain indefinitely after the mine is exhausted after an estimated 17 years of operation, and its rupture is believed capable of provoking a catastrophe equal to that provoked by the 2015 Mariana mine-tailings disaster on the Rio Doce in Minas Gerais (Tófoli et al., 2017). It would release over 35 million m\(^3\) of tailings containing cyanide used for extracting the gold (Emerman, 2020).

Bauxite mining and the processing of the ore to produce alumina and then aluminum can release toxic fines 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 & 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, 2010a; 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 from 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 the Amazon 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) and in the sand of a beach on the coast of the Amazon region (Martinelli Filho & 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 in 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). The amount of plastic transported by Amazonian rivers, from the Andean piedmont down to the mouth of the Amazon River, has not yet been quantified. A substantial accumulation of plastic litter and microplastics has recently been quantified on a river beach in Ecuadorian Amazon (Lucas-Solis et al., 2021).

Many cities, towns, and municipalities that populate rivers and tributaries 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 annually 32,000–64,000 tons of plastic into the Atlantic Ocean (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 Amazon freshwater ecosystems, and current development trends imply dramatic increases in these impacts (Castello & 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 & 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 the 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 result in aquatic ecosystems receiving runoff containing fertilizers, herbicides, pesticides and sediment from soil erosion (Section 6.1 in this chapter). The effect of waterways in reducing transportation costs and inducing replacement of pasture by soy results in indirect land-use change, where cattle ranchers sell their land to soy farmers and move to other parts of the Amazon to clear forest for cattle pasture (Arima et al., 2011; Fearnside, 2015c) (See Chapters 14 and 15).

One of the impacts of waterways is that they serve to justify hydroelectric dams regardless of how severe the impacts of the dams may be. Without a complete sequence of dams on a river, the entire waterway would cease to function because the barges cannot pass the rapids and waterfalls that would be eliminated by the reservoirs. The Tocantins/Araguaia waterway (Fearnside 2002b) (Fearnside, 2002b) and the Tapajós waterway (Fearnside, 2015c) both serve as examples. In the case of the Madeira River, a plan for 4000 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 Interocine Highway has had a dual impact on the rivers and associated terrestrial ecosystems. As shown by satellite imagery analyzed by the MAAP project, this road has promoted land-use change due to agriculture 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 in the length of the dry season will likely 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% for 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 temperature and reduced oxygen concentration 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 & 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 & Almeida-Val, 1995; Almeida-Val et al., 2006; Wootton, 2012). The surplus energy spent in compensating for increased thermal conditions will therefore come at the expense of growth and reproduction and is likely to increase susceptibility to disease (Ficke et al., 2007; Freitas et al., 2012; Oliveira & Val, 2017; Costa & 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 & Bickford, 2011), and this is also expected in fishes (Cheung et al., 2013; Oliveira & Val, 2017; Pauly & 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 et al., 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 the ecosystem services that have local, regional, and global impacts (e.g., fisheries for food security, sediment transport, and carbon sequestration).

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

20.13 Recommendations

- No more Amazon dams with installed capacity \( \geq 10 \) MW should be built. Dams with installed capacity < 10 MW for a single town or village can be built with proper environmental licensing and using a risk-based approach. Rather than building Amazonian dams, energy policy should prioritize electricity conservation, halt exports of electro-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 on infrastructure projects should be reformed such that direct and indirect environmental and social impacts are compiled and democratically debated before decisions are made in practice.
• Selected watersheds throughout Amazonia 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. Inter-basin 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 Amazon 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 encouragement of cooperative arrangements to manage their use (including exclusion of outside fishing vessels) and enforcement of restrictions on overharvesting.

• Proper accounting of the greenhouse-gas emissions of Amazon dams is needed.

20.14 References


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