onservation of Freshwater Fishes

## 5

# Chemical pollution

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## 5.1 INTRODUCTION

Chemical forms of water pollution are a major cause of freshwater habitat degradation worldwide. There are many sources of toxic contaminants, and these reflect past and present human activities and land uses. Toxics can have adverse health impacts on all components of aquatic ecosystems, including threatened fish species and the biological communities they rely on, particularly for food. Toxics can also interact in complex ways with other non-chemical habitat stressors such as water temperature, disease vectors and non-native species (Chapter 2). Therefore, chemical pollution poses important challenges for the conservation of freshwater fish and their habitats. The pollution problem scales roughly in proportion to the global human population, and is therefore expected to grow in significance throughout many parts of the world in the first half of the twenty-first century.

This chapter provides an introduction to freshwater pollution science, with an emphasis on current and emerging threats to vulnerable fish populations. There are now more than 80,000 individual chemicals in societal use, derived from commercial product manufacturing, drug development, pest control practices and many other processes that underpin modern economies. A large fraction of these chemicals eventually ends up in aquatic habitats via direct discharges, land-based run-off and atmospheric deposition. An overview of water quality threats on a chemical-by-chemical basis is impracticable. Rather, we will focus on central themes in freshwater ecotoxicology and common challenges for the conservation and recovery of threatened fish. Additional important

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Table 5.1 *Definitions of key terms used in Chapter 5.*

| Term | Definition |
|---|---|
| Biota | Living organisms, e.g. plants, animals, bacteria |
| Pollution/contaminant | A chemical not naturally found in the environment or found at concentrations not normally present |
| Point source | Originating from identifiable, unique sources such as effluent from a sewage treatment plant or an industrial discharge pipe |
| Non-point source | Originating from dispersed sources such as agricultural lands, residential areas, public spaces, vehicles |
| Persistent contaminant | A chemical that degrades very slowly in the environment, e.g. PCBs |
| Persistent bioaccumulative toxicant (PBT) | Any contaminant taken up by biota faster than it is metabolised and discharged |
| Persistent organic pollutant (POP) | Organic contaminants that are persistent, toxic, undergo long-range transport and bioaccumulate, e.g. organochlorines such as PCBs and dioxins, organometalloids such as methylmercury or tributyltin |
| Legacy contaminant | Persistent contaminants from past industrial, commercial and/or agricultural practices, e.g. PCBs, DDTs |
| Half-life | Time required for a contaminant to decrease to half its initial concentration, e.g. the half-life of methylmercury in aquatic organisms is approximately 72 days |
| Trophic transfer | Contaminant transfer to higher trophic levels through dietary intake, e.g. transfer of PCBs to killer whales from salmon prey, usually resulting in bioaccumulation and biomagnification |
| Bioaccumulation | Accumulation of a contaminant in an individual organism due to faster uptake (ingestion with food or absorption from water) than elimination (metaboliation and excretion) |
| Biomagnification | Accumulation of a contaminant at higher trophic levels in a food web due to transfer from prey to predator |
| Environmental fate | The destiny of a contaminant after release into the environment, e.g. partitioning into air, soil, water |
| Chemical metabolism/ biotransformation | Process whereby contaminants in an organism are chemically altered to facilitate excretion |
| Direct toxicity | Caused by a contaminant acting at a physiological site on or in an organism |
| Indirect toxicity | Caused by a change in the physical, chemical or biological environment, e.g. food web-mediated effects |

challenge to this day. These chemicals were widely used in society until it was discovered they were toxic to humans and wildlife, after which many were banned. They include the early organochlorine insecticides, the most widely known of which is dichlorodiphenyltrichloroethane, or DDT. The discovery of DDT's insecticidal properties led to a Nobel Prize in 1948, and use rates worldwide soared in the decades that followed, initially as part of public health campaigns to control mosquito-borne illnesses such as malaria, typhus and dengue fever. Concurrently, DDT and related organochlorines (e.g. chlordane, aldrin, dieldrin, endrin and mirex) saw increasing use as agricultural insecticides. However, growing concerns over environmental impacts culminated in the publication of Rachel Carson's landmark book *Silent Spring* in 1962, which led to a large public outcry and an eventual ban on DDT for agricultural use in the US in 1972. In 2001, the use of DDT in agriculture was banned worldwide by the Stockholm Convention on Persistent Organic Pollutants.

The persistent organic pollutant category of toxics also includes the polychlorinated biphenyls, or PCBs. These chemicals were incorporated widely into industrial coolant fluids for transformers, capacitors and other electrical equipment, with manufacturing peaking in the 1960s. They were eventually found to cause cancer and other adverse effects in humans, birds, fish and other wildlife, and were banned in the US in 1979. In the years since the US ban and similar restrictions in many other countries, environmental surveillance has shown that PCBs remain measurable in the tissues of fish around the world, with levels particularly elevated in freshwater systems near sites of PCB manufacture or disposal. The effects of PCBs on fish health are myriad. In addition to carcinogenesis, for example, they disrupt immune system function, thereby rendering exposed fish more susceptible to disease.

The persistent pollutants are so-named because they resist degradation in the environment, by processes that are either biotic (e.g. microbial breakdown) or abiotic (e.g. photolysis in response to sunlight). They often accumulate in sediments, and can be resuspended and redistributed in aquatic habitats by burrowing aquatic animals (bioturbation), severe storms and scour, and by dredging and similar forms of human disturbance. As a consequence of their persistence, levels in aquatic systems have been slow to decline, even over decadal timescales. In addition to dispersal in water and through eroded soils, persistent organic pollutants are spread globally by atmospheric transport. Consequently, these contaminants are present in fish habitats that are otherwise pristine.

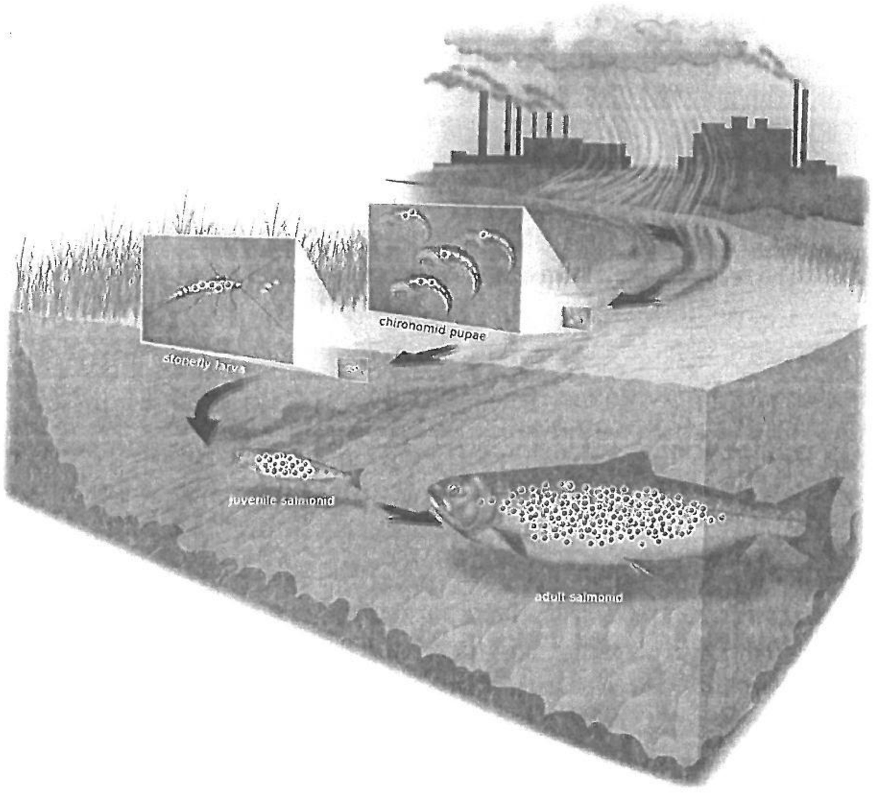

**Figure 5.2** Persistent organic pollutants are transported to aquatic ecosystems from industrial discharges, atmospheric deposition, surface run-off and the erosion or resuspension of historically contaminated sediments. Persistent chemicals resist environmental degradation and accumulate in living organisms. Biomagnification occurs as they are transferred up food webs, thereby concentrating at higher trophic levels. This is illustrated here as the movement of contaminants (circles) in a representative freshwater food web, from chironomid pupae to stoneflies, and to juvenile salmonids that are ultimately eaten by a top fish predator. Exposure risks for persistent pollutants are therefore greater for fish that feed at higher trophic levels.

with millions of juvenile trout yielded adult fish but no sustainable natural recruitment. Several decades later, it was discovered that lake trout embryos are very sensitive to the toxic effects of TCDD at very low exposure concentrations – i.e. in the low parts per trillion (Walker *et al.*, 1991). TCDD causes a range of developmental defects, including heart abnormalities and craniofacial deformities, and these sublethal effects ultimately lead to mortality at the fry stage. Lake trout are long-lived top predators, and bioaccumulated TCDD is maternally transferred from reproductively mature females to embryos (Walker *et al.*, 1994).

of consumption of fish (Mozaffarian & Rimm, 2006). Lastly, legacy contaminants periodically become a new challenge for fish conservation when they are remobilised by modern human activities. Examples include the dredging of contaminated sediments (common near waterfronts with a history of heavy industry) and the removal of dams that releases sediments contaminated with DDT and other toxics (see Chapter 4).

### 5.3 EXPANDING FROM POINT SOURCES TO NON-POINT SOURCES OF POLLUTION

'Point source' and 'non-point source' are phrases in water quality science that distinguish between discharges from a discrete location and more spatially diffuse sources. Non-point sources of pollution are primarily in the form of land-based run-off, but can also include atmospheric inputs directly to water bodies. The line between point and non-point sources is indistinct at times; for example, many stormwater conveyance systems collect contaminants in surface run-off from urban landscapes (diffuse sources) and discharge these to a river or a lake at a discrete location, usually a pipe. Nevertheless, the distinction is meaningful from the standpoint of our evolving understanding of toxic exposures and corresponding consequences for the health of threatened fish species and their habitats.

Throughout most of the world, regulations to protect water quality were weak or non-existent until the latter half of the twentieth century. Lakes and rivers served as receiving waters, or conduits for dumping toxic waste. Hence the common phrase, 'the solution to pollution is dilution'. In developed countries, the Industrial Revolution had a major impact on freshwater and sediment quality. In the US, rivers became so polluted that several actually caught fire (Hartig, 2010). A notable example is the burning of the Cuyahoga River in Cleveland in 1969, an event so egregious it helped rally public support for the eventual passage of the Clean Water Act in 1972. Over the four decades that followed, the Clean Water Act proved effective at reducing end-of-pipe discharges to freshwater habitats. In the restored Cuyahoga River, for example, fish communities have transformed from a few pollution-tolerant species, such as the gizzard shad (*Dorosoma cepedianum*), to more diverse and abundant assemblage dominated by pollution-sensitive species (e.g. spotfin shiner, *Notropis spilopterus*) (Rahel, 2010). The gradual reversal of the industrial river syndrome as a positive response to point-source and toxic plants for insect control, and in the Middle Ages arsenic and mercury were commonly applied. Natural products were subsequently developed as pesticides, most notably pyrethrum (pyrethrins) from chrysanthemums and nicotine sulphate from the leaves of tobacco plants. In the mid-twentieth century, arsenic-based and natural products gave way to synthetic pesticides, including the aforementioned DDT and related organochlorines. Many of the pesticides in modern use are synthetic derivatives of earlier natural products, including the pyrethroid and neonicotinoid insecticides that are chemically related to pyrethrin and nicotine, respectively. As an aside, agricultural uses of neonicotinoids (e.g. imidacloprid) have received considerable attention in recent years for their implication in the recent 'colony collapse disorder' among honeybees in North America and Europe. Because of the high risk to pollinators, and therefore the agricultural economy, they were banned by the European Union in 2013.

The term 'pesticide' encompasses a large diversity of chemicals that target specific taxa – i.e. insecticides, herbicides, algaecides, fungicides, rodenticides, avicides, molluscicides, nematicides, miticides and piscicides (e.g. rotenone, also a natural plant derivative). There are hundreds of different pesticides currently used worldwide, applied in more than a thousand different product formulations. These uses go far beyond agriculture, and include commercial and residential pest control, right-of-way maintenance, disease vector control, aquatic vegetation removal, forestry management and invasive species control. From the standpoint of threatened fish, the use of pesticides (primarily herbicides) to kill non-native species via in-water or riparian zone applications creates a trade-off between the known habitat benefits of chemical control and the often poorly understood potential for toxicity to fish and other so-call non-target species (Stehr *et al.*, 2009).

This section will focus on agricultural pesticides, and current use insecticides in particular, as these are generally more toxic to freshwater fish and their prey. The ongoing effort to recover threatened and endangered Pacific salmon populations in western North America serves as a case example of pesticide risks to imperilled fish species. Pacific salmonids are highly migratory, and include distinct population segments of Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*) and steelhead (*O. mykiss*), several of which are currently listed for protection under the United States Endangered Species Act (for species status and range, see National Marine Fisheries Service listings at www.nmfs.noaa.gov/pr/species/esa/fish.htm). Salmonids with stream-type life histories spend a improve the resiliency of food webs for fish, and enhance the likelihood that more conventional physical habitat restoration activities are successful (Naiman *et al.*, 2012).

### 5.5 URBAN RUN-OFF

By most measures, the biological integrity of urban watersheds is poor. This 'urban stream syndrome' has been widely documented (reviewed by Walsh *et al.*, 2005) and is attributable to physical, biological and chemical forms of habitat degradation. The science in recent decades has focused to a large extent on hydrologic and geomorphic changes at the catchment and drainage scales, including altered flows, sedimentation and loss of streambed substrates, channel incision and loss of side channel habitat, and non-chemical changes in water quality (e.g. increasing stream temperatures). In some cases, stream headwaters are simply buried (Elmore & Kaushal, 2008). Recurring biological impacts include a loss of functioning riparian streamside habitat and the invasion of non-native species. Toxics have received comparatively less attention, in part because urban stormwater run-off is exceptionally complicated in terms of chemical composition. Also, in cities with ageing infrastructure, severe storms deliver stormwater mixed with wastewater in combined sewer overflows.

The multitude of pressures on urban stream habitats presents significant challenges for stream restoration efforts (Bernhardt & Palmer, 2007). Moreover, non-urban watersheds (forested, grassland, desert, etc.) that presently support viable fish populations are widely vulnerable to the impacts of future urbanisation, in tandem with projected climate change (e.g. Nelson *et al.*, 2008). In cities worldwide, urban run-off is consistently toxic to fish and stream invertebrates (e.g. McIntyre *et al.*, 2014, 2015). Depending on how, when and where within a watershed the stormwater is collected, the toxicity is variously attributable to metals from motor vehicle brake pads; petroleum hydrocarbons (polycyclic aromatic hydrocarbons, or PAHs) from vehicle emissions of oil, grease, and exhaust; de-icing salts; residential and commercial pesticide use; metals from building materials (e.g. zinc and copper from metal galvanised roofs and treated wood); and a large diversity of toxics that are deposited atmospherically in urban environments, including mercury, PBDEs and plasticisers (phthalates).

Chemical pollution in urban stormwater has the potential to undermine fish habitat restoration efforts that focus exclusively on physical antibiotics, perfumes, nanoparticles and any other chemicals that go down a household drain are potential CECs. In rural areas, these same chemicals can enter streams and lakes from more diffuse sources, for example through the hyporheic inflow of groundwater contaminated by leaky septic systems. Concentrated animal feeding operations (CAFOs) for cattle, pigs and poultry are also important sources of CECs in run-off, particularly where antibiotics and growth hormones are used to maximise agricultural yield. Notably, CECs are not always new or emerging chemicals; on occasion, new scientific information raises concerns over familiar chemicals – e.g. the toxicity of imidacloprid to honeybees and the ensuing European ban, as mentioned earlier.

Many CECs are hormones or hormone mimics that cause endocrine disruption in fish, particularly oestrogens, androgens and their chemical antagonists. Much of the initial work on wastewater-driven impacts grew out of studies in the UK. Upon discovering hermaphroditic fish in sewage treatment lagoons, researchers subsequently showed that effluent contained oestrogenic compounds that caused an upregulation of vitellogen in the plasma of caged rainbow trout (Purdom *et al.*, 1994). Vitellogenin, an egg yolk protein normally produced only by females, has since proven to be a very sensitive bioindicator of oestrogenic endocrine disruption in male fish from freshwater and marine habitats around the world. Field assessments in the UK (Jobling *et al.*, 1998) demonstrated high frequencies of intersexuality (feminised male fish) in wild populations of the riverine roach (*Rutilus rutilus*). Although most wild intersex roach are able to breed, their reproductive success is impaired in proportion to the extent of their feminisation (Harris *et al.*, 2011). Although there are many oestrogenic CECs, much of the research over the past two decades has focused on the potent oestrogen ethynylestradiol, derived from birth control pills. In a landmark study, Canadian scientists working at the Experimental Lakes Area in northwestern Ontario conducted an ecosystem assessment of endocrine disruption by releasing low levels of ethynylestradiol into an otherwise pristine experimental lake over the course of three years. The chronic exposure to ethynylestradiol feminised resident male flathead minnows (*Pimephales promelas*), as evidenced by vitellogenin induction and intersex gonadal development, and in subsequent years the minnow population in the lake collapsed (Kidd *et al.*, 2007). More broadly, the theme of endocrine disruption in fish and other species has grown to be one of the most active research areas in aquatic ecotoxicology (Sumpter, 2005).

of neuroactive CECs altering the physiology and behaviour of fish in effluent-impacted habitats are likely to grow in the years ahead.

### 5.7 RESOURCE EXTRACTION AND TRANSPORT

Throughout the world there have been relatively massive and usually unintended inputs of toxics to freshwater ecosystems. These can be caused by natural disasters, such as earthquakes, floods and hurricanes. In 2006, for example, the winds and floodwaters from Hurricane Katrina in the USA caused hundreds of onshore releases of petroleum and other hazardous substances to Lake Pontchartrain and the Mississippi River in the vicinity of New Orleans (Santella *et al.*, 2010). Other disasters, including those caused by warfare, are human-caused. Often these involve industrial accidents such as the fire that consumed a pesticide manufacturing facility near Basel, Switzerland in 1986. More than 1300 metric tons of various pesticides, solvents and intermediate chemicals were stored in the facility; and large volumes were washed into the Rhine River as the blaze was battled (Capel *et al.*, 1998). The results were catastrophic, with massive die-offs of eels, salmonids and other aquatic life for hundreds of kilometres downriver through Germany and the Netherlands. Natural disasters and the ensuing human response can sometimes intermix to cause fish kills. This includes, for example, the use of toxic fire retardants and foams to suppress wildfires across the globe (e.g. Adams & Simmons, 1999).

Large-scale pollution inputs that are a consequence of natural resource extraction and transport pose considerable past, present and future threats to the conservation of freshwater fishes. Certain forms of extraction (e.g. in-river gravel mining) have overtly negative impacts on fish habitats. A prominent example is the worldwide increase in surface mining. In the Appalachian region of the eastern US, for example, so-called 'mountaintop removal' is used to access buried seams of coal. The overlying deciduous forest and topsoil are removed and explosives are used to break up the underlying rock. The debris buries nearby stream headwaters ('valley fill'), thereby destroying habitat for endemic fishes (Palmer *et al.*, 2010). Furthermore, the loss of vegetation and topsoil reduces rainwater infiltration, leading to substantial increases in storm run-off and downstream flooding. Water flowing out of valley fills is chemically degraded in many ways, including increased levels of sulphuric acid, metals and selenium (Palmer *et al.*, 2013). A bioaccumulative contaminant, selenium is widely known to be toxic to wildlife. In then flowed downstream unchecked into the Doñana National Park, a UNESCO World Heritage Site (Grimalt *et al.*, 1999). A few years later, in 2000, a dike holding back millions of litres of cyanide-laced water failed in the Romanian gold mining town of Baia Mare. The ensuing toxic plume entered the Tisza River and devastated in-river aquatic life across Hungary en route to the Danube River delta, hundreds of kilometres distant on the shores of the Black Sea (Koenig, 2000). Fish species endemic to the Tisza were nearly eradicated, and the disaster had a significant impact on the ˜ 60 fish taxa downstream, a third of which were in a protected status. The question of whether past disasters are a prologue for the future is currently under debate in Alaska, where a huge open-pit copper, gold, and molybdenum mining project (known familiarly as Pebble) is currently proposed in the headwaters of Bristol Bay. The pristine headwater river systems in the vicinity of the proposed mining support the largest salmon run in the world, and the world's largest commercial sockeye (*O. nerka*) fishery.

The extraction and transport of petroleum products, particularly crude oil, is also a worldwide threat to freshwater habitats. Crude oils from different geological sources all contain PAHs that cause various adverse health effects in fish, including cancer (Myers *et al.*, 2003) and immunotoxicity (Reynaud & Deschaux, 2006). Moreover, research in the aftermath of the 1989 *Exxon Valdez* oil spill in Prince William Sound, Alaska, has shown that marine and freshwater fish embryos are exceptionally sensitive to the cardiotoxic effects of PAHs. Transient low-level exposures cause heart failure during embryogenesis (Incardona *et al.*, 2011), and fish that survive have cardiovascular abnormalities that reduce cardiac output and swimming performance later in life (Hicken *et al.*, 2011).

Oil exploration, extraction and transport have polluted many freshwater systems in recent decades. Seepage from production pits and failing infrastructure has created a major environmental problem in the Ecuadorian Amazon (e.g. Wernersson, 2004). The controversial development of oil sands in northern Alberta, Canada, has polluted the Athabasca River with PAHs and a variety of metals (e.g. Kelly *et al.*, 2010). The heavy crude oil from the Athabasca tar sands has proven especially difficult to clean up, as evidenced by the expense and complexity of restoration efforts in the Kalamazoo River following the 2010 pipeline disaster in Michigan, the largest on-land oil spill in US history. Pipeline infrastructure is also a major issue in Nigeria, where thousands of crude and refined oil spills have occurred in the Niger River delta

Green stormwater infrastructure, or low-impact development, encompasses a suite of strategies and technologies to capture and, where possible, detoxify pollutants in stormwater run-off before they reach rivers, lakes and streams. Green infrastructure is primarily used in urban watersheds in situations where source control is not possible. The approaches fall into the categories of green roofs, permeable pavements and bioretention (Dietz, 2007; Ahiablame *et al.*, 2012). All use soil to filter particulate-bound and dissolved-phase contaminants. For metals, removal success using green infrastructure can be quite high (e.g. up to 99% for zinc; Davis *et al.*, 2009). Moreover, field assessments of bioretention effectiveness in dense urban areas report large removals of PAHs (87%; DiBlasi *et al.*, 2009) and motor oil (up to 96%; Chapman & Horner, 2010). Retained or sorbed organic contaminants such as PAHs are often biodegraded in soils through microbial processes (LeFevre *et al.*, 2012). Notably, green infrastructure may not be as effective for some CECs. For example, in a study with five pharmaceuticals, carbamazepine and gemfibrozil were found to be relatively mobile in soils and more resistant to degradation (Yu *et al.*, 2013).

Lastly, green chemistry describes a set of guidelines for conducting chemical reactions in industrial processes that minimise harm to the environment, including aquatic habitats. These principles promote reusable catalysts, safe solvents (i.e. water), energy efficiency, and the use of chemicals that break down into non-toxic substances (Ahuja & Hristovski, 2013). Green chemistry is proving increasingly useful for minimising industrial forms of water pollution, as well as restoring water and sediment quality in aquatic systems that have been impacted by legacy contamination. As an example, ferrate(VI) is a powerful oxidant that undergoes a reaction and conversion into a non-toxic byproduct, Fe(III) (Sharma, 2002). Ferrate(VI) can be successfully substituted for weaker and more toxic oxidants such as permanganate, ozone and hypochlorite to break down anionic surfactants (Eng *et al.*, 2006), endocrine-disrupting toxicants (Jiang *et al.*, 2005) and pharmaceuticals (Sharma & Mishra, 2006; Sharma *et al.*, 2006), among other contaminants.

## 5.9 CHEMICAL POLLUTION AND FRESHWATER FISH CONSERVATION: A LOOK FORWARD

This chapter has provided a broad overview of toxic chemical threats to freshwater fishes and their habitats. While pollution continues to be change, instream flow diversions, etc.). In effect, less dilution will make it more difficult to find solutions to pollution.

To meet these challenges, conservation biologists focusing on freshwater fishes and chemical pollution will need a diverse toolbox of knowledge and skills. This toolbox necessarily spans several disciplines that have traditionally been somewhat distinct. For example, conservation biologists, fisheries biologists and ecotoxicologists typically train in separate academic departments. They join scientific societies and attend conferences that often have minimal substantive overlap. In the USA, for example, these include the Society for Conservation Biology, the American Fisheries Society and the Society of Environmental Toxicology and Chemistry. This separation leads in turn to the partitioning of new scientific information in discipline-specific journals. For example, the journal *Conservation Biology* rarely features pollution studies. Conversely, advances at the leading edge of theory and practice in conservation biology are rarely published in *Aquatic Toxicology*. On the path forward to freshwater fish conservation, modern scientific institutions have become barriers to collaboration, innovation and the effective exchange of new ideas and technologies. In the practice of conservation, this makes it very difficult to assess the side-by-side importance of pollution and other habitat factors (water quantity, invasive species, temperature, etc.) as limiting factors for the recovery of imperilled fish species. A different approach is needed, beginning with a more diverse and inclusive curriculum for undergraduate and graduate training programmes.

Technology is expected to play an outsized role in pollution science in the near-term. Methods for analytical chemistry are improving constantly, allowing for the detection of more and more chemicals at ever-lower concentrations in water, sediments and fish tissues. This conveys an increasingly accurate picture of chemical habitat quality, and has been the impetus for the recent expansion of new research on the environmental occurrence and toxicity of pharmaceuticals, nanomaterials and other CECs. A key challenge ahead is the development of real-time observing systems for toxics, to circumvent the need to bring discrete samples back to a laboratory for analyses that may take days or weeks. These observing systems are in place for other water-quality parameters (e.g. temperature, conductivity) and, increasingly, for pathogenic biological organisms. *In situ* observing systems for toxics will have numerous applications, from early warning to integrated profiling of complex non-point source pollution. For example, a monoclonal antibody-based biosensor was recently used to monitor the real-time resuspension of contaminants on aquatic ecosystems. The challenge ahead will be to mine large data sets via bioinformatics. New and meaningful information about fish health will still need to be scaled, to forecast impacts on wild populations and changes in the dynamics of aquatic communities. An emerging framework for this is the increasing use of 'adverse outcome pathways' (AOPs), which sequentially link a molecular initiating event to endpoints at the individual or population level in ways that are relevant for ecological risk assessment (e.g. growth, survival, reproduction) (Ankley *et al.*, 2010).

In closing, chemical pollution science continues to be a dynamic and evolving facet of freshwater conservation biology. Habitat pressures are likely to expand in many areas of the world in response to ongoing human population growth and industrialisation (Bakker, 2012). New technologies are revealing new threats to endangered fish species, and new strategies are being implemented to reduce toxic run-off and restore degraded habitats. Many fish populations are resilient, and begin a positive recovery trajectory when pollution sources are controlled. Collaboration is essential, across the disciplines of environmental chemistry, molecular biology, physiology, animal behaviour, experimental ecology, fisheries biology, mathematical modelling, geographic information systems, computational informatics, social science, natural resource policy, conservation management and environmental law. Future conservationists should prepare to study genes, ecosystems and everything in between.

## 5.10 DISCUSSION QUESTIONS

1. Which sets of laws in your country are intended to protect threatened freshwater fishes from the harmful effects of chemical pollution? How much protection do they afford?
2. What is the concept of a sentinel species, and how are sentinels used in freshwater ecotoxicology?
3. In the larger picture of habitat pollution as it relates to species conservation, what is the role of the environmental chemist? How is this changing?
4. How might the life history of a particular threatened fish species influence its vulnerability to chemical contaminants?
5. Designing studies to address chemical mixtures has been an enormous challenge in ecotoxicology for decades. How might emerging technologies change this?

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