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Coastal Storms, Toxic Runoff, and the Sustainable Conservation of Fish and Fisheries

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Abstract.—Nonpoint source pollution in the form of stormwater runoff is one of the most important emerging threats to ecosystems along the coastal margins of the United States. A wide diversity of potentially toxic chemicals is commonly found in stormwater. These include the various pesticides, petroleum hydrocarbons, heavy metals, and other common contaminants that originate from commercial, industrial, residential, and agricultural land-use activities. These chemicals are mobilized from roads, lawns, crops, and other surfaces by rainfall and then transported to aquatic habitats via terrestrial runoff. The ongoing development of coastal watersheds nationwide is increasing the loading of nonpoint source pollutants to rivers, estuaries, and the nearshore marine environment. A central aim of the National Oceanic and Atmospheric Administration's national Coastal Storms Program (CSP) is to enhance the resiliency of coastal ecosystems by improving the ability of coastal communities to anticipate and reduce the impacts of contaminated terrestrial runoff. Toxic chemicals in stormwater can adversely impact the health of fish, including threatened and endangered species. Nonpoint source pollution can also degrade the biological integrity of aquatic communities that support productive fish populations. This article examines the effects of stormwater runoff on fish and fisheries. Using case studies drawn from CSP project work in the Pacific Northwest and Southern California pilot regions, we show how degraded water quality can impact the health of fish during critical life history stages (i.e., spawning and rearing) as well as limit the overall effectiveness of fish habitat restoration. We also discuss some of the resources currently available to local communities to reduce the loading of toxics in stormwater, thereby increasing the resilience of aquatic communities. Finally, we identify priority areas for new research to help guide the future conservation and recovery of at-risk fish populations.

> Coastal waters are one of the nation's greatest assets, yet they are being bombarded with pollutants from a variety of sources. While progress has been made in reducing point sources of pollution, nonpoint source pollution has increased and is the primary cause of nutrient enrichment, hypoxia, harmful algal blooms, toxic contaminants, and other problems that plague coastal waters. Nonpoint source pollution occurs when rainfall and snowmelt wash pollutants such as fertilizers, pesticides, bacteria, viruses, pet waste, sediments, oil, chemicals, and litter into our rivers and coastal waters… Our failure to manage the human activities that affect the nation's oceans is compromising their ecological integrity, diminishing our ability to fully realize their potential, costing us jobs and revenue, threatening human health, and putting our future at risk (U.S. Commission on Ocean Policy 2004).
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> Today, nonpoint sources represent the greatest pollution threat to our oceans and coasts. Every acre of farmland and stretch of road in a watershed is a non-

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point source. Every treated lawn in America contributes toxics and nutrients to our coasts… the situation requires that we apply new thinking about the connection between the land and the sea, and the role watersheds play in providing habitat and reducing pollution (Pew Oceans Commission 2003).

Introduction

Human population growth and associated changes in land use are placing ever-increasing pressures on coastal ecosystems. At present, more than 50% of the U.S. population resides in coastal counties, which together account for only 17% of the total geographical area of the country (Crossett et al. 2004). While the relative proportion of people living near America's coasts is expected to remain relatively constant, growth projections forecast a nearly 50% increase in the overall size of the U.S. population by 2050 (Day 1996). These growth trends are expected to drive new development along America's coastlines, thereby increasing the loading of nonpoint source pollutants to rivers, estuaries, and the nearshore marine environment.

Variation in land cover and land use within a coastal drainage typically determines the presence and relative amounts of different chemical contaminants in stormwater runoff (Tsihrintzis and Hamid 1997; Bay et al. 2003). For example, pesticides are typically detected in small streams and other surface waters in proportion to their rate of application within watersheds (Gilliom et al. 2006). Urban runoff generally contains heavy metals and petroleum hydrocarbons from motor vehicles and commercial land uses; pesticides from residential, park, and golf course applications; and pharmaceuticals from combined sewer overflows where these occur. In agricultural areas, nonpoint source runoff generally contains a greater diversity of pesticides, as well as pathogens and nutrients (Hunt et al. 1999). Various factors affect pollutant loading and transport to aquatic systems, such as length of the antecedent dry period, rates of atmospheric deposition, storm intensity, soil composition, and ground cover (Bertrand-Krajewski et al. 1998; Goonetilleke et al. 2005; Han et al. 2006).

An increase in impervious land cover within watersheds poses a key threat to aquatic ecosystems (Paul and Meyer 2001; Nilsson et al. 2003). Examples of impervious surfaces include paved roads, highways, parking lots, driveways, and roofs. A variety of indicators have consistently shown that the biological condition of aquatic habitats is significantly degraded when the total impervious area of a watershed exceeds 10% (reviewed by Beach 2002). This is notable because the current amount of impervious coverage in watersheds throughout the country is estimated to range from 12.5% to 30% (Beach 2002). Moreover, several studies have shown a negative correlation between urbanization and aquatic species diversity and abundance (Karr 1991; Booth et al. 2002; Wheeler et al. 2005). Although correlations between urbanization and aquatic habitat degradation are now widely established (Weaver and Garman 1994; Walsh et al. 2005a, 2005b; Urban et al. 2006; Gresens et al. 2007; Schiff and Beniot 2007), the causal contribution of chemical contaminants relative to physical processes (i.e., hydrology and geomorphology) remains poorly understood.

Despite the fact that nonpoint source pollution is an increasingly important determinant of aquatic habitat quality, the impacts of toxic runoff on the productivity of wild fish populations have not been widely investigated. This is due in part to the complex environmental chemistry of stormwater. Storms can mobilize unpredictable mixtures of contaminants over relatively short time intervals. Another challenge in recent decades has been a difficulty linking sublethal health effects in individual fish to the higher biological scales of populations and communities (Hinton et al. 2005). While nonpoint source pollution occasionally causes fish kills, most contaminant exposures are sublethal. This basic fact indicates a need to understand how toxics influence the physiology and behavior of fish in ways that ultimately determine their lifetime reproductive success (Scott and Sloman 2004). This in turn places a greater emphasis on the ecology of fish, for example, how toxics influence predator–prey interactions, disease susceptibility, migration, and other important life history processes (Rohr et al. 2006). Therefore, to effectively maintain (or restore) the resilience of aquatic ecosystems in the face of development pressures, coastal communities and natural resource managers need new scientific information specific to the ecotoxicological effects of stormwater.

This article addresses the impacts of toxic stormwater on fish and fisheries. To explore this issue, we draw from recent field investigations and contaminant-specific toxicological research to assess the impacts of stormwater on the health of fish in California and the Pacific Northwest. These studies were conducted as part of the the National Oceanic and Atmospheric Administration's (NOAA) national Coastal Storms Program (http://www.csc.noaa.gov/csp/) with the aim of more clearly defining the current and future threats posed by toxic runoff to fish habitats. This article is not intended as a review of the toxicological literature. Also, we do not discuss the extent to which pollution may limit specific fisheries. Our goal instead is to highlight different approaches that have been used to link real-world habitat conditions to the health and survival of fish. We also give examples of how emerging biotechnologies are making it easier to resolve subtle but important health effects in fish and to unravel some of the complexities associated with chemical mixtures.

Three specific case studies are highlighted in the following sections. The first describes unexpectedly high rates of acute mortality among adult Pacific salmon returning to spawn in restored urban streams in the greater Seattle metropolitan area. The findings are a cautionary tale for urban stream restoration. They reinforce the importance of in situ biological monitoring in aquatic systems impacted by urban runoff. They also foreshadow potential future threats to wild salmon populations in developing watersheds in northern California and the Pacific Northwest. The second case study shows how one of the most common contaminants in stormwater (dissolved-phase copper) can isolate juvenile salmon from important sensory cues in their surrounding environment, thereby increasing their vulnerability to predation. It serves as an example of how short-term, environmentally realistic pulses of pollution in fish habitats can disrupt the physiology and behavior of fish and how sublethal effects can be extrapolated to higher biological scales. The third case study gives an overview of new exploratory research to discover novel pathways of toxicity in fish during sensitive life stages. The focus is on petroleum hydrocarbons, which originate from motor vehicles (and other sources) and are ubiquitous in urban runoff. We show how an expanding toolbox of techniques in molecular biology and genetics can be used to (1) address the complicated problem of chemical mixtures, and (2) identify previously unknown biological response pathways. Among other applications, these new technologies may lead to new and sensitive indicators of health and performance in wild fish exposed to hydrocarbons in urbanizing waterways. Following the case studies, we identify some tools available to local communities for reducing the loading of toxics in stormwater, thereby increasing the resilience of aquatic communities. We close with a discussion of research priorities that will help guide the future conservation and recovery of fish and fisheries that are impacted by stormwater runoff.

Recurrent Die-Offs of Coho Salmon Returning to Spawn in Restored Urban Streams

As in other regions of United States, current growth in the Pacific Northwest is driving the conversion of forested and agricultural lands to commercial and residential uses. These changes in land cover and land use are posing increasingly important threats to anadromous Pacific salmon (genus *Oncorhynchus*) species that are significant throughout the region for commercial, recreational, cultural, and ecological reasons (National Research Council 1996). Among these are several stocks of Chinook salmon *O. tshawytscha*, sockeye salmon *O. nerka*, coho salmon

O. kisutch, chum salmon *O. keta*, pink salmon *O. gorbuscha*, and steelhead *O. mykiss*. Due in part to the degradation and loss of habitat, many salmonid stocks have been declining in recent decades (Nehlsen et al. 1991). As a consequence, several salmonid population segments, or evolutionarily significant units (ESUs), are now listed as either threatened or endangered under the U.S. Endangered Species Act (for current species listings, see http://www.nmfs.noaa.gov/pr/). For example, the lower Columbia River coho and Puget Sound steelhead ESUs were listed as threatened in 2006 and 2007, respectively. In response to these numerous and geographically widespread listings of salmon populations, a major societal effort is now underway to conserve and restore freshwater and estuarine habitats.

On a more local scale, urban and suburban streams in and around cities such as Seattle, Washington have been the focus of intensive restoration activities for more than a decade. The efforts to date have been largely focused on replanting native riparian vegetation, increasing habitat complexity using weirs and large woody debris, removing culverts and other barriers to fish passage, and increasing stormwater detention in urban areas. As with many high-density regions (reviewed by Paul and Meyer 2001), lowland streams in the Seattle metropolitan area receive significant amounts of nonpoint source pollution that increase along a gradient of urbanization. Outfalls from storm drains make up a significant fraction of surface flows in these streams, particularly during the fall and winter months. Therefore, stream restoration projects have had to contend with the familiar hydrologic challenges associated with stormwater management (Bernhardt and Palmer 2007).

A key benchmark for the success of urban stream restoration projects throughout lowland Puget Sound has been the extent to which adult salmonids (primarily coho and chum) return to spawn in the improved and, in some cases, newly available habitats. Beginning in the late 1990s, field biologists with the city of Seattle, Washington Trout (since renamed the Wild Fish Conservancy), and other organizations made a surprising discovery. They found that while salmon were successfully returning to many restored streams, a high proportion of sexually mature female coho carcasses, when examined, showed large numbers of retained eggs (Figure 1). They went on to document highly erratic swimming behavior and prespawn mortality among both male and female coho. Affected fish from different urban streams displayed a common suite of symptoms, including surface swimming and gaping, fin splaying, spasming, disorientation, and loss of equilibrium. The coho usually died within a few minutes to a few hours after becoming overtly symptomatic. Visual inspections generally indicated that the affected coho spawners were in good condition, with the silver coloration typical of salmonids that have recently transitioned to freshwater from the ocean.

The ad hoc observations of coho prespawn mortality (PSM) during fall spawner surveys prompted a focused monitoring and forensic research study. The investigation began in 2002 and has continued in the years since as part of the NOAA's Coastal Storms Program project work in the Pacific Northwest. To date, 5 years of daily stream surveys have been conducted during coho spawner migrations in the fall on Longfellow Creek in west Seattle (Figure 2A). The Longfellow drainage, a typical urban stream system, has been a focus for intensive habitat restoration in recent years. Daily surveys have also been conducted on other Seattle-area urban streams. In 2002, adult coho mortality was monitored on Fortson Creek, a nonurban forested tributary of the north fork of the Stillaguamish River as a reference location (Figure 2B). Coho spawning habitat was surveyed for live, symptomatic, and dead animals. For all dead or symptomatic female coho, the location, species, gender, length, weight, and spawning condition (percentage egg retention in females) were recorded. Spawning condition was only assessed for female coho because of the difficulty determining whether field-collected males had spawned. Rainfall and instream flow data were also collected for the different streams.

Figure 1. Dead adult coho salmon that was found in Longfellow Creek following a rain event in December 2005. This female died prior to spawning, as demonstrated by the 75–100% egg retention. Photo by Sarah McCarthy, NOAA Fisheries.

After a protracted dry period in the early fall of 2002, adult coho salmon began entering Longfellow Creek with the first major rains and ensuing freshets in early November. All of the females returning to the stream in the first several days died before spawning, and successful spawners were only observed after several significant rain events. The overall rate of female PSM for Longfellow Creek in 2002 was 86.0% (n = 57 animals) across the entire fall run. At the nonurban location (Fortson Creek), nearly all of the returning female coho survived to spawn, with an overall female PSM rate of 0.01% (n = 114). Surveys

Figure 2. Study sites for coho salmon prespawn mortality investigations. (A) Longfellow Creek is a restored stream located in a highly residential and commercial area in West Seattle, Washington and was sampled daily during the fall coho spawning season, 2002–2006. (B) Fortson Creek is a nonurban forested tributary of the North Fork Stillaguamish River, near Darrington, Washington and was sampled daily during the coho run in late fall and winter, 2002. Photographs by Carla Stehr, NOAA Fisheries.

in subsequent years have revealed similarly high rates of PSM in Longfellow Creek (Table 1; N. Scholz, NOAA Fisheries, Northwest Fisheries Science Center, unpublished results) as well as other urban streams in the lowland Puget Sound geographic area. Within Longfellow Creek, the severity of coho die-offs from year to year appears to be influenced by rainfall. Preliminary results from survey data gathered thus far indicate a significant inverse relationship between total rainfall during the fall spawning season and coho PSM (Scholz, unpublished results). The highest rates of spawner mortality were observed in fall seasons that were relatively dry but punctuated by episodic storm events. Monitoring of rainfall and PSM rates will continue in Longfellow Creek over the next several years to better define the relationship between fall weather patterns, transport of contaminants in stormwater, and coho PSM.

Coho PSM in urban streams is unlikely to be causally related to other types of prespawn mortality in salmonids that have previously been associated with high temperature, low dissolved oxygen, overcrowding, disease, parasites, predation, or an accidental chemical spill (e.g., Gilhousen 1990; Heard 1991; California Department of Fish and Game 2004; Quinn 2005). In recent years, surface water quality monitoring and a variety of forensic analyses of affected coho from Longfellow Creek have systematically ruled out each of these hypotheses (Scholz, unpublished results). Instead, the weight of evidence suggests that adult coho are acutely sensitive to nonpoint source stormwater runoff from urban landscapes. Whether salmon are dying from exposure to a single contaminant or a mixture of contaminants is not yet known. On the one hand, most pollutants are present in urban surface waters at concentrations below those that will typically cause fish kills. On the other hand, coho spawners undergo important physiological changes as they transition from saltwater to freshwater. These changes may render them more vulnerable to toxic chemicals, alone or in combination with other environmental stressors. Research to identify the precise cause of coho PSM is ongoing.

Table 1. Annual rates of female coho pre-spawn mortality (PSM) in an urban stream (Longfellow Creek, West Seattle, Washington) and a forested reference stream (Fortson Creek, north fork Stillaguamish River, Washington). Sample size (*N*) indicates number of dead females of known spawning condition, not including fish that were preyed upon prior to sample date. Percentage calculated as number of PSM females divided by number of pre- and postspawn mortality females

Site	Year	*N*	%PSM
	2002	57	86
	2003	18	66.7
Longfellow Creek	2004	9	88.9
	2005	75	72
	2006	4	100
Fortson Creek	2007	114	0.01

The "urban stream syndrome" comprises a suite of common characteristics that include flashy flow regimes during storms, increased sedimentation, higher levels of contaminants, and low abundance and survival of sensitive aquatic species. This creates a tendency for systems that drain highly urbanized areas to be degraded despite localized restoration efforts (Walsh et al. 2005b). The restoration activities on Longfellow Creek were successful in terms of attracting spawning coho back to the watershed. However, postconstruction monitoring has revealed that many spawners are unable to withstand pollutants in urban stormwater runoff. These findings reinforce the current view that urban stream restoration projects need to address the physical, chemical, and biological aspects of habitat quality at appropriate scales (Booth et al. 2004; Walsh et al. 2005a; Bernhardt and Palmer 2007). It is particularly important that water quality be considered at the catchment scale.

In closing, there are several important lessons to be learned from research to date on coho PSM. First, biological monitoring is an essential component of aquatic habitat restoration. We are now aware of the threats that urban runoff poses for coho populations because postconstruction field surveys revealed the anomalous behavior and condition of spawners attracted to restored streams. Second, degraded water quality in the form of nonpoint source pollution has the potential to undermine restoration activities in urban areas that focus exclusively on physical and biological habitat processes. Third, conventional laboratory toxicity studies may not adequately capture real-world threats to fish in highly complex chemical environments such as urban streams. Finally, nonpoint source pollution is likely to become an increasingly important issue for the sustainable conservation of wild coho populations in urbanizing watersheds throughout the western United States. Models are currently being developed to identify at-risk river systems in the Puget Sound region and to forecast the potential for local coho extinctions over the next several decades of human population growth and development.

Dissolved Copper and the Salmon Nose

Dissolved copper is one of the most ubiquitous contaminants in stormwater runoff to aquatic systems. This reflects the many societal uses of copper in coastal watersheds. These include, for example, the incorporation of copper into roofing materials, pesticide formulations, antifoulant paint for boats, and treated wood. In urbanizing areas, one of the most important sources of copper is automobiles. Vehicle exhaust contains copper, and the action of braking releases trace amounts of copper and other heavy metals from brake pads. Copper accumulates on highways, roads, parking lots, and similar surfaces until storm events mobilize the metal in runoff. Since conventional detention and treatment systems for runoff are designed to reduce the impacts of sedimentation and altered flow, they typically do not remove dissolved-phase copper from surface waters. Therefore, because of its close association with cars and roads, copper is in many ways a signature contaminant for urban and suburban development.

Research sponsored by NOAA's Coastal Storms Program has recently focused on the impacts of dissolved copper in stormwater on salmon and steelhead in the Pacific Northwest pilot region. Copper is classically known to be highly toxic to many aquatic organisms. At high concentrations, the metal is acutely lethal to fish via a mechanism that involves the binding of copper to the gill (Niyogi and Wood 2004). Much less is known about the sublethal effects of copper, particularly following short-term exposures (i.e., on the order of hours) that are more typical of episodic stormwater runoff events. A key management concern related to runoff from impervious surfaces is whether transient, environmentally realistic exposures to copper interfere with the life history requirements of threatened or endangered salmonids in the Pacific Northwest and, more recently, in California. A related challenge has been to link sublethal effects to the survival and reproductive success of individual animals, as these processes determine the productivity and recovery potential of Ecological Society of America (ESA)-listed populations.

Recent NOAA research has focused on the salmon olfactory nervous system as an important target for dissolved-phase copper. It has been known for more than 30 years that the chemosensory system of fish is particularly vulnerable to the neurotoxic effects of copper (Hara et al. 1976; Hansen et al. 1999a). This is due, in part, to the direct contact between sensory neurons in the olfactory epithelium (the olfactory rosette; Figure 3) and pollutants in surface waters. The potential for olfactory neurotoxicity raises several important concerns for anadromous salmonids, as these species rely on chemical signals in the aquatic environment to imprint on their natal streams, detect and avoid predators, navigate during adult migrations, and synchronize their spawning. There are also several logistical advantages to focusing on the salmon nose for toxicity studies. For example, the biology of olfaction in fish has been actively studied for many years, and the basic architecture and function of the peripheral olfactory epithelium is well understood (Hara 1992) relative to many other areas of the fish nervous

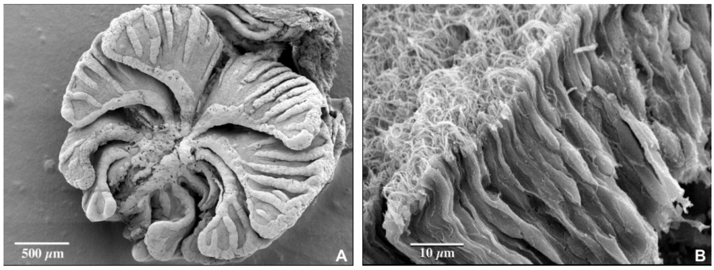

Figure 3. Features of the coho salmon peripheral olfactory system. (A) Scanning electron micrograph showing an entire olfactory rosette from a juvenile coho salmon. Each of the lamellae (major folds) is covered in an epithelium that includes regions of sensory neurons. (B) Scanning electron micrograph showing a cross section of the sensory epithelium along a single lamella. In the upper left is the apical surface containing the cilia and microvilli of the olfactory receptor neurons. Photographs by Carla Stehr, NOAA Fisheries.

system. Receptor neurons are very sensitive to chemical cues, and their responsiveness to a variety of natural odorants is well documented. Finally, straightforward electrophysiological methods have been established for monitoring the effects of pollutants on the active properties of sensory neurons (Baldwin and Scholz 2005). The salmon nose is therefore an experimentally tractable system with a high degree of biological relevance for individual survival, migration, and reproduction.

Much of the recent work to date has focused on freshwater-phase juvenile salmon, as juveniles spend months to years (depending on the species) in small stream catchments that are most likely to be affected by stormwater runoff. Salmonids are known to avoid gradients of copper in aquatic habitats, such as those that might be produced by municipal point-source discharges, irrigation return flows, or direct discharges from mining activities (Hansen et al. 1999b). However, the diffuse loading of copper to streams via runoff is a form of nonpoint source pollution. In the absence of a distinct gradient, it is unlikely that salmon will be able to avoid copper from nonpoint sources.

As expected from previous work with other fish species (e.g., Hara et al. 1976), dissolved copper is a potent inhibitor of olfactory function in juvenile coho salmon (Baldwin et al. 2003). When exposed to environmentally relevant copper concentrations (0–20 parts per billion), salmon olfactory neurons become increasingly unresponsive to natural odorants (e.g., the amino acid L-serine) in a dose-dependent manner. The onset of functional anosmia occurs within the first few minutes of exposure, a window that is well within the typical duration of a stormwater pulse. Another significant finding from initial research is that the olfactory toxicity of copper is similar across receptor neurons that respond to different classes of odorants (Baldwin et al. 2003). Not surprisingly, reduced electrical activity in the peripheral sensory epithelium translates to a reduction in the response of neural networks in the olfactory forebrain (Sandahl et al. 2004). Because copper appears to be a general-purpose inhibitor of chemoreception in salmon, it has the potential to interfere with many if not all behaviors that depend on a normally functioning olfactory system.

Many studies have now shown that copper disrupts olfactory function in fish. However, the extent to which laboratory observations of physiological impairment are predictive of effects on critical behaviors has only recently been investigated. To explore the relative effects of copper on the neurobiology and behavior of juvenile coho, Sandahl et al. (2007) devised a computer-assisted imaging system to monitor the predator avoidance behavior of individual animals in response to a chemical alarm signal. Like many other species of fish, juvenile salmon have within their skin specialized cells that contain a chemical alarm substance. When a predator attacks a fish, the mechanical tearing of the skin releases the alarm cue into the surrounding water. The cue signals a predation risk to nearby conspecifics, and neighboring fish respond with a stereotypical suite of avoidance behaviors, the most prominent of which for salmon is a tendency to become motionless (Brown and Smith 1997; Scholz et al. 2000). The alarm response of juvenile salmon is both robust and ecologically relevant and is therefore particularly well suited for investigating the olfactory toxicity of copper.

Using a combination of neurophysiological and behavioral recording methods, Sandahl et al. (2007) compared the effects of copper on olfaction and olfactory-mediated predator avoidance behaviors in juvenile coho salmon. A short-term (3 h) exposure was chosen to emulate environmental exposures to copper in stormwater runoff. The inhibitory effects of copper (at or above 2 μg/L) on olfactory receptor neurons correlated very closely with a loss of responsiveness to the predation cue (Sandahl et al. 2007; Figure 4). Therefore, short-term exposures to copper are sufficient to isolate juvenile salmon from important features of their sensory landscape. While copper exposures may not kill fish outright, sensory deprivation has the potential to increase mortality rates due to predation during freshwater rearing stages. This is important because even modest changes in overall rates of juvenile mortality can significantly influence the productivity of wild salmon populations (Kareiva et al. 2000).

In summary, Coastal Storms Program research on copper was designed to provide resource managers with targeted new information about one of the most common contaminants, urban stormwater runoff. The findings should have applications in geographical areas outside of the Pacific Northwest. For example, the results in coho salmon have recently been extended to steelhead (D. Baldwin and N. Scholz, NOAA Fisheries, Northwest Fisheries Science Center, unpublished results), which are presently endangered in Southern California. Future research chal-

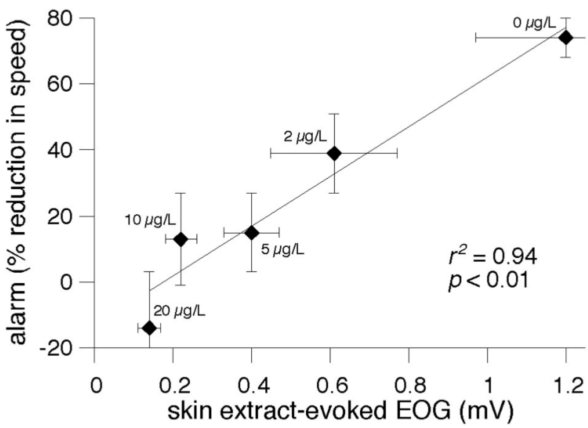

Figure 4. Exposure to copper diminished both olfactory sensitivity and alarm behavior in juvenile coho (figure from Sandahl et al. 2007). Electro-olfactogram (EOG) responses to skin extract (10 μg protein/L) were inhibited at increasing copper concentrations. Copper exposure also reduced the behavioral alarm response elicited by 0.1 μg protein/L of skin extract in a dose-dependent manner. Paired physiological and behavioral response means were highly correlated (i.e., fish with reduced olfactory sensitivity showed reduced alarm behavior). Error bars represent one standard error bar.

lenges include linking the behavioral effects of copper to more refined estimates of individual survival and reproductive success (e.g., field studies of homing and straying behavior in migratory adults [Scholz et al. 2000]). These challenges notwithstanding, it is now reasonably well established that copper in stormwater runoff has the potential to limit the recovery of ESA-listed salmon populations. This is likely to place an increasingly important emphasis on stormwater management strategies that reduce the loading of copper and other dissolved toxicants.

Polycyclic Aromatic Hydrocarbons and the Developing Fish Heart

Fossil fuel use contributes a large suite of potentially toxic compounds to runoff from impervious surfaces. Although polycyclic aromatic hydrocarbons (PAHs; Figure 5A) represent a small fraction of the total hydrocarbon mass of fossil fuel products, some PAHs are known to be highly toxic to fish. The increase in the number of motor vehicles over the last decade has resulted in a corresponding increase in the loading of PAHs to aquatic habitats (Van Metre et al. 2000; Lima et al. 2002; National Research Council 2003; Partridge et al. 2005). Airborne PAH levels are generally proportional to human population densities (Hafner et al. 2005), and deposition of airborne PAHs is now the largest source of aquatic contamination (Van Metre et al. 2000; Lima et al. 2002; Van Metre and Mahler 2003; Li and Daler 2004). In addition, runoff from impervious surfaces can also contain PAHs from other sources, such as gasoline, lubricating oils, and coal tar- or asphalt-based parking lot sealants (Mahler et al. 2005). Although stormwater contributes a smaller fraction of the total aquatic PAH loadings relative to other routes of transport (e.g., direct absorption of gas-phase PAHs [Gigliotti et al. 2002, 2005]), storm events can raise PAH levels in streams dramatically, thereby contributing significantly to the levels of PAHs in estuaries and other nearshore areas, particularly in sediments (Hoffman et al. 1984; Crunkilton and DeVita 1997; Menzie et al. 2002; Hwang and Foster 2006; Kimbrough and Dickhut 2006; Stein et al. 2006).

Although the sources, transport and accumulation of PAHs in coastal habitats have been extensively monitored, the biological impacts of PAHs on fish have received comparatively less attention. Moreover, the potential role for PAHs in stormwater as a limiting factor for the productivity of fisheries resources is not well understood. However, two intensive lines of investigation in previous years have shown that PAHs are a potential threat to the health of fish. The first is the well-documented effects of carcinogenic PAHs on benthic fish living in close association with historically contaminated sediments in the nearshore marine environment. The second is the impact of crude oil-derived PAHs on fish at early life history stages, an understanding gained to a large degree from research conducted on Pacific herring Clupea pallasii and pink salmon after the *Exxon Valdez* oil spill in Prince William Sound, Alaska. Oil spill research on herring and salmon led to the discovery of previously unrecognized pathways of toxicity involving the fish heart. More generally, these studies have underscored how little is known about the biological effects of PAHs. A much more sophisticated view of PAH toxicity has been emerging in recent years, and, with this, a recognition that predicting the effects of this complex family of compounds will require an expanded research effort. As discussed below, these data gaps have been a key focus for new research sponsored by the NOAA's Coastal Storms Program.

PAHs occur in stormwater in highly complex mixtures that vary considerably in composition depending on the relative contributions from petrogenic (e.g., oil) or pyrogenic (i.e., combustive) sources (Figure 5B). In general, petroleum products are enriched with low molecular weight PAHs containing two or three rings, while fuel combustion products contain a higher percentage and variety of high molecular weight compounds with four rings or more (Wang et al. 2003; Lima et al. 2005). Because most low molecular weight PAHs are found as multiple alkylated

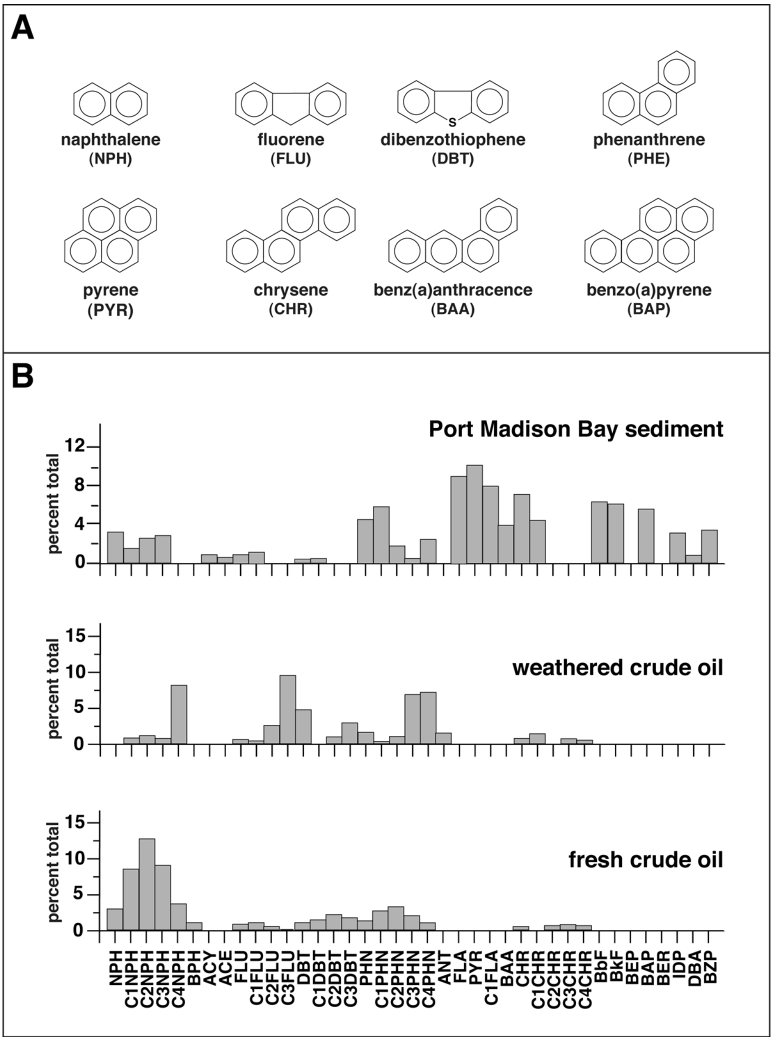

Figure 5. PAH structures and distribution of PAHs from different sources. (A) Representative examples of PAHs commonly found in aquatic environments. PAH heterocycles include the sulfur-containing dibenzothiophene. Some PAHs are alkylated to various degrees, usually with methyl groups (see below). (B) PAH distributions in fresh Alaska North Slope crude oil (bottom), weathered Alaska North Slope crude oil (middle), and sediments from a shallow, enclosed bay on Bainbridge Island near Seattle, WA (top). Each bar represents the percent of total PAH for each compound detected by gas chromatography/mass spectrometry, with molecular weight increasing to the right on the x-axis. Groups are color coded for two-, three-, four-, and five- or six-ring compounds according the scheme in (A). Compounds are abbreviated as in (A) and degree of methylation is indicated by C1, C2, and so forth. (e.g., C2PHN is dimethylphenanthrene). For alkylated PAHs, each bar represents a mixture of isoforms that are methylated at different positions. PAH analysis of Port Madison Bay sediment courtesy of Jim West and Sandie O'Neill, Washington Department of Fish and Wildlife.

isomers, PAH mixtures can contain hundreds of individual compounds. This high degree of complexity raises at least three major research challenges that are highly relevant to the conservation of fisheries. The first is delineating the relationship between the toxicity of individual PAH compounds and the toxicity of complex mixtures. It is now becoming clear that different compounds affect the health of fish via different biological pathways. Are there toxicological effects that stem uniquely from PAH mixtures, and do these vary with the overall composition of mixtures? The second is to link low-level PAH inputs in stormwater to the health and survival of individual fish and, by extension, to the productivity of vulnerable fish populations. This challenge is identical in most respects to the research objectives identified for dissolved copper in the preceding section. The third is to develop new diagnostic tools that can be used to assess the health of PAH-exposed fish under natural conditions. These new biological indicators, which are increasingly needed for ecosystem-based monitoring systems throughout coastal regions of the United States, should ideally be both sensitive and specific for PAH toxicity.

Studies on the toxicology of PAHs began early in the 20th century with the identification of benzo[a]pyrene as the primary causative agent of cancers associated with coal tar exposure (Phillips 1983). High molecular weight (five- and six-ring) PAHs such as benzo[a]pyrene are potent procarcinogens activated by metabolism through the aryl hydrocarbon receptor (AHR)–cytochrome P4501A (CYP1A) pathway. The AHR is a ligand-activated transcription factor that controls the expression of a battery of genes encoding enzymes that convert PAHs to water-soluble derivates that are excreted, including mixed function oxygenases such as CYP1A family members (Schmidt and Bradfield 1996; Nebert et al. 2004). CYP1A oxidizes PAHs, converting some to reactive intermediates that can alkylate DNA (and other macromolecules), leading to somatic mutations and neoplasia. One of the most clearly delineated cause–effect relationships for PAH impacts on fish is the association of exposure to PAH-contaminated sediment with neoplastic liver lesions in benthic species such as English sole Pleuronectes vetulus (Myers et al. 2003). PAH toxicity is generally considered in these terms, but as described below, this traditional view belies the true complexity of this large family of compounds.

The toxicity of low molecular weight PAHs, which are weak AHR ligands, was largely unappreciated until the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska. Similarly, this event shifted the research focus from adult fish to early life history stages. The *Exxon Valdez* oil spill coincided with the seasonal spawning of Pacific herring Clupea pallasi and was followed shortly after by the spawning of pink salmon O. gorbuscha. By nature of their preferred spawning habitat, these two species deposited eggs in areas that were most heavily contaminated by the spill (Peterson et al. 2003; Short et al. 2003). Alaska North Slope crude oil (and most other crude oils) contain a PAH fraction that is dominated by two- and three-ring compounds, but in which the carcinogenic high molecular weight compounds are absent or present in only trace amounts (Wang et al. 2003). Over the last decade, many studies examining the effects of dissolved petroleum-derived PAHs on development of herring, pink salmon, and other fish species documented a common malformation syndrome as well as significant sublethal effects in the absence of malformations, including reduced growth and survival to adulthood (Marty et al. 1997; Carls et al. 1999; Heintz et al. 1999, 2000; Couillard 2002; Peterson et al. 2003). Other studies in recent years have also shown that fish embryos and larvae are highly sensitive to PAH mixtures from a variety of other sources, including creosote wood preservatives, oil sands, and sediments impacted by urbanization (Vines et al. 2000; Ownby et al. 2002; Colavecchia et al. 2004; Wassenberg and Di Giulio 2004; Sundberg et al. 2005).

Recent research supported by NOAA's Coastal Storms Program has focused on using the zebrafish Danio rerio model system to identify the specific contributions of different PAHs to early life stage toxicity in fish. Zebrafish have become a major experimental model in environmental health research, in large part because of the advanced suite of genetic and molecular tools available for developmental biology (Shin and Fishman 2002). A systematic comparison of the effects of individual PAHs to weathered crude oil led to the identification of at least three distinct modes of action for PAH developmental toxicity in fish (Incardona et al. 2004, 2005, 2006). This was largely possible due to the rapid development and accessibility of the zebrafish embryo allowing continuous monitoring of organogenesis and to the suite of genetic and molecular tools associated with the zebrafish system (Shin and Fishman 2002). Notably, research using zebrafish has produced a sophisticated understanding of the links between form and function in the developing fish heart (Glickman and Yelon 2002), which was found to be the primary target of low molecular weight PAH toxicity (Incardona et al. 2004).

Weathered crude oil and tricyclic PAHs (fluorene, dibenzothiophene, and phenanthrene) were found to cause cardiac dysfunction soon after the heart becomes active, which has multiple secondary consequences for cardiac morphogenesis. The heart is one of the first organs to be functional in the embryos of fish and other vertebrates. Because cardiac function and morphogenesis are inextricably linked, any disruption of cardiac physiology during early development ultimately impacts the subsequent shape of the heart. Consequently, developing embryos exposed continuously to cardiac toxins have hearts that fail to develop and become atretic (string-like), ultimately leading to the structural defects previously associated with exposure to petroleum hydrocarbons. In this case, genetic analysis using zebrafish embryos indicated that the AHR-CYP1A pathway played a protective rather than causal role in toxicity and that these tricyclic PAHs are directly cardiotoxic (Incardona et al. 2004, 2005). Potential targets for petrogenic tricyclic PAHs include ion channels, structural proteins, or regulatory enzymes involved in the cardiac contraction cycle.

In distinct contrast to individual tricyclic PAHs or weathered crude oil, the four-ring pyrogenic PAH benz[a]anthracene acts through the AHR pathway to cause a different type of heart malformation, in the same manner as more potent AHR ligands such as dioxin (Prasch et al. 2003; Teraoka et al. 2003; Carney et al. 2004; Antkiewicz et al. 2005). A third type of toxicity was observed with exposure to another pyrogenic four-ring compound, pyrene, which resulted in systemic toxicity that was dependent on metabolism by CYP1A in the liver (Incardona et al. 2006). Other high molecular weight PAHs that are abundant in stormwater have not yet been characterized at this level of detail, although their potency as AHR ligands suggests that they would act similarly to benz[a]anthracene.

In summary, deciphering the toxicology of PAH mixtures in stormwater has proven to be a complex research challenge. Investigations to date have shown that the developing fish heart is vulnerable to a variety of impacts from multiple members of the PAH family, each acting through distinct cellular pathways. These findings have been a major step forward in terms of understanding how PAHs affect the health of fish, alone and in mixtures. The discovery that the heart is a primary target organ also represents a significant advance towards the eventual goal of developing new diagnostic tools for assessing the health of fish throughout coastal areas of the United States. However, there are still a large number of PAH compounds whose individual toxicity is unknown, and PAH mixtures in stormwater are more complicated than purely petrogenic mixtures represented by oil spill models. The immediate embryonic effects of exposure to a handful of individual PAHs and petrogenic PAH mixtures are now understood in fair detail, but more information is needed on the long-term impacts of transient sublethal exposure and effects of exposure in later larval and juvenile stages. The effects of more complex mixtures representative of urbanized sediments are also unknown, and it is unclear how pathways of petrogenic and pyrogenic PAH toxicity might interact. Research findings in zebrafish need to be validated in native species. To this end, studies on early life stage Pacific herring and California halibut *Paralichthys californicus* are now underway as part of the NOAA's Coastal Storms Program. Ultimately, a full appreciation of the impacts of urbanization and stormwater runoff on key marine and aquatic resources will require a more detailed understanding of mechanisms of PAH toxicity. Because survival of early life history stages is crucial for recruitment to adult populations, particularly at low population sizes (Myers et al. 1999), there is considerable potential for population-level impacts stemming from the myriad sublethal physiological effects of these compounds.

Achieving Resilience in Coastal Ecosystems

Resilience, a central theme in ecology, refers to the capacity of ecosystems to maintain structure and function in the face of a disturbance or a sustained forcing pressure such as development (Holling 1973; Walker et al. 2004). Human activities such as overfishing can decrease resilience, thereby increasing the potential for an ecosystem to undergo undesired regime shifts (Folke et al. 2004). For example, a coral reef in a highly impacted area may become more susceptible to disease and bleaching, causing a shift to a reef dominated by algae (Folke et al. 2004). As is evident from recent research on coho salmon in Pacific Northwest urban streams, nonpoint source pollution poses some important and difficult challenges to local efforts aimed at improving the resilience of aquatic habitats.

Effective mitigation strategies are essential in vulnerable areas that are impacted by degraded runoff. Coastal areas are not only important in terms of natural ecosystem function, they are also highly coveted by humans for economic and esthetic reasons and thus can be referred to as social-ecological systems. Therefore, as a human element is introduced, the ability of the resource managers to mitigate for resilience and prevent the ecosystem from reaching a critical threshold becomes integral (Walker et al. 2004). Stormwater management techniques may need to vary according to the vulnerability or current state of the target ecosystem. For some specific land uses, it may be less important to document the nature and extent of the toxicological injury to fish than to conduct research to help understand which source control measures are most effective. This includes, for example, using biologically based methods to monitor the effectiveness of stormwater filtration, riparian buffers, low impact development, and other mitigation options. In most cases, source control for contaminants is very expensive, and the benefits that these resource management options provide to aquatic species are not well understood.

As an example of NOAA's sponsorship of new technologies to promote resilience, the Cooperative Institute for Coastal and Estuarine Environmental Technology has funded targeted research on the development and efficiency of stormwater management techniques that help protect nearshore aquatic environments from degraded runoff (http://ciceet.unh.edu/). Among their funding recipients is the University of New Hampshire Stormwater Center (http://www.unh.edu/erg/cstev/). They have installed 11 different stormwater devices at their research facility and provide fact sheets on the results of their research for planners, engineers, researchers, and restoration practitioners who are deciding among technology choices. Information on manufactured devices (such as infiltration devices and manhole retrofits), filters, bioretention systems, gravel wetlands, and porous pavement also give practitioners the ability to compare technologies and choose the one that best fits their land use and site in terms of which contaminants need to be removed, project budget, and available physical space.

Future Research Priorities

Society currently lacks much of the scientific information needed to manage nonpoint source pollution and reduce the impacts of toxic stormwater runoff on coastal fisheries. The rapid rate of current development along the coastlines of the United States (Paul and Meyer 2001; Beach 2002; Nilsson et al. 2003; Crossett et al. 2004) represents a persistent forcing pressure that will continue to degrade the quality of spawning, rearing, and migratory habitats for fish. In addition, the success or failure of habitat restoration activities throughout the country will hinge, in part, on an understanding of the limitations imposed by nonpoint source pollution. This is true for restoration in urban areas (Simenstad et al. 2005) as well as in geographical regions that will become urban or suburban in the next few decades (Bernhardt and Palmer 2007). The trend towards more impervious surfaces in coastal watersheds is going to make it increasingly difficult to maintain resilient fish populations. Unfortunately, climate change is likely to complicate this task even further. Climate change and pollution are expected to combine in terms of their threats to fisheries (Schindler 2001). This is particularly true for terrestrial runoff, as this is largely driven by the frequency and intensity of storms. Below, we identify priority areas for new research, modeling, and risk assessment. Advances in each of these areas will substantially improve the scientific foundation for sustaining fish populations and the ecosystems that support them.

Studying Individual Animals while Managing Populations

Conservation and recovery planning for vulnerable coastal fisheries typically occurs at the scale of natural populations and, increasingly, at the level of communities and ecosystems (Arkema et al. 2006). An enduring challenge in ecotoxicology is to link the health of individual animals to these higher scales. To this end, population models are playing an increasingly important role (Spromberg and Meador 2006). To align empirical studies with quantitative models, future research should provide the biological and demographic information necessary to model how real-world exposures to toxics in terrestrial runoff might alter the lifetime reproductive success of individuals within a population. These population models can then be used to forecast future extinction risks associated with nonpoint source pollution and also to estimate the relative importance of surface runoff as an obstacle to habitat recovery in coastal watersheds and estuaries.

A Need for More "Eco" in Ecotoxicology

Assessing and predicting the community-level effects of toxics is a challenge that is becoming progressively more important in community ecology (Rohr et al. 2006). Contaminants can have a wide variety of indirect effects on fish and fisheries in coastal areas. Trophic cascades are a common source of indirect effects (Fleeger et al. 2003), and these can lead in turn to decreased prey availability and starvation (Bennet et al. 1995) among other outcomes. Other examples of indirect effects include increased vulnerability to predation (Labenia et al. 2006), disease susceptibility and pathogen-induced mortality (Arkoosh et al. 2001), and competition with nonnative, contaminant-tolerant species. Understanding the impacts of terrestrial runoff on these and other ecological processes will invariably require more "eco" in the field of ecotoxicology, that is, combining a multispecies approach to research with new advances in community-based modeling.

Evaluating Single Chemicals in a World of Multiple Stressors

For decades, conventional toxicological investigations have typically focused on the adverse health effects of individual contaminants. As shown by the earlier example of copper and salmon olfaction, this approach can yield useful information on priority contaminants in stormwater. In the real world, however, nonpoint source pollution almost always involves the delivery of complex mixtures of chemicals to aquatic habitats. These mixtures, combined with other (nonchemical) stressors, can impact the health of fish in ways that are highly unpredictable and still poorly understood. For example, an interactive effect of multiple stressors may explain the unexpected mortality of adult salmon returning to spawn in Pacific Northwest urban streams. Moreover, since current-use pesticides frequently occur as mixtures in streams (Hoffman et al. 2000), Coastal Storms Program research has focused on the interactive toxicity of pesticides in mixtures (Scholz et al. 2006). This has led recently to the unexpected finding that some mixtures of common insecticides produce synergistic (i.e., greater than additive) neurotoxicity and mortality in juvenile salmon (C. Laetz and N. Scholz, NOAA Fisheries, Northwest Fisheries Science Center, unpublished results). Also, as noted earlier, the impacts of contaminants on fish survival can be proportionately greater when fish are coexposed to toxics and another environmental stressor such as a pathogen (Arkoosh et al. 2001; Clifford et al. 2005). Understanding and minimizing the effects of multiple stressors is one of the major research challenges in modern ecotoxicology (Eggen et al. 2004). The associated complexity is one of the primary reasons why resource management agencies have had such difficulty confronting nonpoint source pollution (U.S. Commission on Ocean Policy 2004).

A Need for Species-Centric Versus hemical-Centric Risk Assessment

Ecological risk assessment is a widely used tool in ecotoxicology. Although risk assessment is a relatively young discipline with many different applications to date, most risk assessments involving toxic substances are chemical-centric. This usually involves assessing the potential toxicity of a single chemical to a wide diversity of aquatic species, often using a classical comparative metric such as the median lethal concentration (LC50). Chemical-centric risk assessments are typically developed to inform specific types of resource management activities. These include, for example, the U.S. Environmental Protection Agency's registration or re-registration of a pesticide, or the development of aquatic life criteria under the Clean Water Act. While chemical-centric risk assessments may be useful for these specific purposes, they are very poorly suited for evaluating the impact of nonpoint source pollution on at-risk fish and fisheries. LC50-based risk assessments may not adequately capture important ecological considerations, including delayed effects, indirect effects, and impacts on sensitive species or life history stages. In the case of threatened or endangered fish populations (i.e., Pacific salmon), the biological requirements of the species are a more appropriate conceptual basis for risk assessments involving polluted stormwater. Species-specific risk assessments are desirable because they incorporate a higher degree of ecological realism. They emphasize the survival potential of a fish in the real world, where a particular chemical is only one of many environmental stressors.

Identifying Cost-Effective Pollution Control Measures and Mitigation Strategies that Work

With a few exceptions, the sources of many nonpoint source pollutants in aquatic habitats are reasonably well known. These include, for example, the heavy metals and petroleum hydrocarbons that originate from motor vehicles. Engineered solutions to surface runoff typically focus on reducing toxic loads. Loading reductions will invariably improve overall water quality, but they may not go far enough to ensure resilience if there is still a sufficient amount of toxic runoff to impact fish and their habitats. Therefore, it will be important to combine emerging technologies for stormwater management with targeted toxicological research, ideally involving the in situ monitoring of fish health as well as other indicators of ecological response.

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