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Contaminants in the Watershed: Implications for Hawaiian Stream Biota

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Abstract

In aquatic systems throughout the world, urban and agricultural activities have resulted in elevated concentrations of organochlorine pesticides and metals. At sites on two Hawaiian Islands, O'ahu and Kaua'i, streambed sediment and fishes were analyzed for organic and metal contaminants; benthic invertebrates were collected for analysis of community composition and structure; and physical habitat characteristics were recorded. Sites were selected to represent a gradient of development from high-intensity urban to undeveloped (forested) areas. Many of the sites had both urban and agricultural development in the watershed. Concentrations of many organic and metal contaminants at the developed sites exceeded criteria for the protection of fish and benthic aquatic invertebrates, and the wildlife that consume them, and indicate potential deleterious effects. Streams in developed watersheds had elevated concentrations of organochlorine pesticides used for termite control (dieldrin and chlordane) and DDT. Concentrations of metals including arsenic, cadmium, lead, and zinc in sediment from developed areas were substantially higher than concentrations measured in undeveloped areas. Differences in macroinvertebrate species composition, diversity, and abundance were associated with elevated concentrations of contaminants at the developed sites compared with the undeveloped sites. The persistence of these contaminants, their tendency to accumulate in sediment and biota, and their potentially harmful effects are of concern for the management and protection of stream biota in Hawaiian watersheds.

Introduction

With increasing population and subsequent development, many watersheds in the Hawaiian Islands have undergone substantial land-use change that has resulted in degradation of both water and habitat quality (Brasher, 2003; Anthony *et al.*, 2004). Anthropogenic influences, both urban and agricultural, can adversely impact stream ecosystems. Effects such as stream channelization for flood control or roadways, increases in sedimentation from construction and farming, contaminants from agricultural, urban, and industrial activities transported in storm-water runoff, and diversions used to redirect stream water to agriculture and other off-stream uses can all affect stream quality (Oki & Brasher, 2003).

As is typical throughout the tropics, modifications of the stream ecosystems have been most severe at the lower elevations where urban growth is greatest (Resh *et al.*, 1992; Pringle & Ramirez, 1998). Urbanization is typically accompanied by stream channelization and the removal of riparian canopy cover that results in higher water temperatures and increased daily temperature fluctuations, as well as increased siltation and removal of larger substrate such as boulders (Brasher, 2003; Brasher *et al.*, 2004). Habitat alteration can have substantial impacts on aquatic communities that reside in the streams, resulting in changes in species composition, abundance, and diversity. Distinct invertebrate assemblages have been observed to occur with different land uses in the watershed and consequently can be used to indicate habitat quality (Brasher *et al.*, 2004).

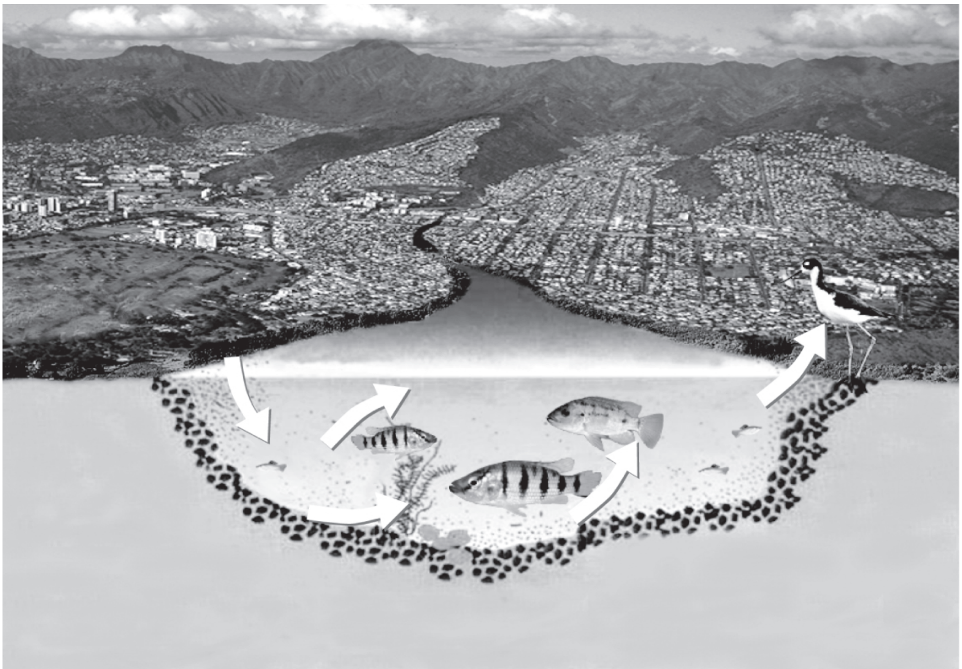

Figure 1. Organochlorine pesticides and metals are transported from agricultural and urban sources through soil erosion, runoff, and precipitation. Once in the stream, they accumulate in streambed sediments and in tissues of aquatic invertebrates and fish.

Physical changes including decreased habitat heterogeneity and increased abiotic variability are compounded by the presence of organic and inorganic (metal) contaminants (Oki & Brasher, 2003). Urban land use is commonly associated with a variety of organochlorine, organophosphate, and metal contaminants in streams. These constituents are applied on land as pesticides, herbicides, or fertilizer, in both urban and agricultural areas, or may have industrial uses. Whether present in the water column or adhered to the sediment, they can have potentially negative effects on the benthic invertebrates that live in the streams (Nowell *et al.*, 1999; Oki & Brasher, 2003; Cain *et al.*, 2004).

Organochlorine pesticides are chlorine-containing compounds that are present in the environment as a result of human activities. Organochlorine pesticides were heavily used from the mid-1940s to the mid-1980s. The persistence of organochlorine pesticides, their tendency to accumulate in soil, sediment, and biota, and their harmful effects on wildlife resulted in restriction or banning of their use in the United States in the 1970s through mid-1980s (Nowell *et al.*, 1999). Despite use restrictions, these compounds continue to be detected in sediment and fish samples.

Metals (for example arsenic, copper, lead, mercury, and zinc) can occur naturally in the environment but may increase to elevated levels as a result of human activities. Urban sources for metals include vehicular traffic, batteries, paint, road surfacing, leaded gasoline, and wood preservatives. Many metals have been shown to be toxic to aquatic biota (Hare, 1992). As with organochlorine pesticides, leaded gasoline and lead-based paints were phased out in the 1970s, but lead persists in soils and continues to enter Hawaiian streams with sediment in runoff (DeCarlo & Anthony, 2002).

Organochlorine pesticides, metals, and trace elements enter the aquatic environment from a variety of sources including the atmosphere, industrial and municipal effluents, and soil erosion and other nonpoint-source runoff (Fig. 1). Once in the system, these compounds (which have low solubility) are mostly associated with bottom sediments that can be ingested by benthic organisms. These organisms are then eaten by fish and birds, transferring the contaminants to higher trophic levels in aquatic and terrestrial food chains.

Table 1. **List of sites samples**.

Site	Code	Island	Pesticides Sediment	Pesticides Fish	Metals Sediment	Metals Inverts
Ala Wai Canal	ALWI	Oʻahu		X		
Hanakāpīʻai Stream	HNKP	Kauaʻi				X
Hulēʻia Stream	HULA	Kauaʻi				X
Kalauao Stream	KALA	Oʻahu	X	X		X
Kalihi Stream (lower)	LKLI	Oʻahu	X	X	X	
Kalihi Stream (upper)	UKLI	Oʻahu	X	X	X	
Kaluanui Stream	KALU	Oʻahu		X	X	X
Kāneʻohe Stream	KANE	Oʻahu	X	X	X	X
Kapaʻa Stream	MKPA	Kauaʻi				X
Kaukonahua Stream	KKON	Oʻahu		X	X	
Kaukonahua Stream (North Fork)	NFKK	Oʻahu			X	
Kaukonahua Stream (South Fork)	SFKK	Oʻahu		X	X	
Keaʻahala Stream	KEAH	Oʻahu		X		
Kīpapa Stream	KIPA	Oʻahu	X	X	X	
Kōloa Stream	KOLO	Oʻahu		X	X	
Lawaʻi Stream (lower)	LLWI	Kauaʻi				X
Lawaʻi Stream (upper)	ULWI	Kauaʻi				X
Limahuli Stream	LMAH	Kauaʻi				X
Luluku Stream	LULU	Oʻahu	X	X	X	X
Makaleha Stream	UKPA	Kauaʻi				X
Mānoa Stream	MANO	Oʻahu	X	X	X	X
Maunawili Stream	MWIL	Oʻahu	X	X	X	
Nawiliwili Stream	NWIL	Kauaʻi	X	X	X	X
Nuʻuanu Stream (lower)	NUUA	Oʻahu	X	X	X	X
Nuʻuanu Stream (upper)	NUUJ	Oʻahu		X		
ʻŌpaʻeula Stream (lower)	LOPA	Oʻahu		X	X	
ʻŌpaʻeula Stream (upper)	UOPA	Oʻahu		X	X	
Poamoho Stream	POAM	Oʻahu	X	X	X	
Pūʻali Stream	PUAL	Kauaʻi		X		X
Punaluʻu Stream (above dam)	PUNA	Oʻahu				X
Punaluʻu Stream (below dam)	PUNB	Oʻahu				X
Wahiawā Reservoir	WAHI	Oʻahu		X	X	
Waiāhole Stream	WHOL	Oʻahu				X
Waiakeakua Stream	WKEA	Oʻahu	X	X	X	X
Waiawa Stream	WAIW	Oʻahu	X	X	X	X
Waiheʻe Stream	WHEE	Oʻahu	X	X	X	X
Waikakalaua Stream	WKAK	Oʻahu	X	X	X	X
Waikele Stream	WKEL	Oʻahu	X	X	X	X
Waimānalo Stream	WAIM	Oʻahu	X	X	X	X
Waimano Stream	WANO	Oʻahu	X	X	X	

Although organisms used in stream-quality monitoring programs include algae, invertebrates, and fish (Lenat & Barbour, 1994; Barbour *et al.*, 1999), benthic macroinvertebrates are by far the most commonly used group of organisms for this purpose (Rosenberg & Resh, 1993). Benthic macroinvertebrates offer many advantages in biomonitoring: (1) they are ubiquitous and, consequently, can be affected by environmental perturbation in a variety of aquatic systems and habitats, (2) the large number of species offers a wide spectrum of responses to environmental stressors, (3) their basic sedentary nature allows effective spatial analyses of pollutants or disturbance effects, and (4) they have relatively long life cycles, which allows elucidation of temporal changes caused by perturbation (Rosenberg & Resh, 1993).

Table 2. Organochlorine compounds and codes used in this paper.

Compound	Code	Compound	Code
Aldrin	ALD	delta-HCH	DHC
cis-Chlordane	CCH	gamma-HCH (Lindane)	LIN
trans-Chlordane	TCH	Heptachlor	HEP
Dacthal (DCPA)	DCP	Heptachlor epoxide	HEE
o,p'-DDD	ODD	Hexachlorobenzene	HEX
p,p'-DDD	PDD	o,p'-Methoxychlor	OME
o,p'-DDE	ODE	p,p'-Methoxychlor	PME
p,p'-DDE	PDE	Mirex	MIR
o,p'-DDT	ODT	cis-Nonachlor	CNO
p,p'-DDT	PDT	trans-Nonachlor	TNO
Dieldrin	DIE	Oxychlordane	OXY
Endrin	END	PCB	PCB
alpha-HCH	AHC	Pentachloroanisole	PEN
beta-HCH	BHC	Toxaphene	TOX

In this paper we discuss streams that are located in watersheds on two Hawaiian islands, O‘ahu and Kaua‘i, and represent a gradient of anthropogenic development from high-intensity urban to undeveloped (forested) areas. We will describe the results of our recent studies assessing organochlorine contaminants, trace elements, and metals in streambed sediment and fish from selected streams on these two islands. Because development frequently results in the co-occurrence of water-quality degradation (including organic and inorganic contaminants) and physical habitat alteration, we will also describe how urbanization affects physical habitat characteristics. Finally, we will discuss implications of stream-quality alteration, associated with anthropogenic activities in the watershed, to the benthic macroinvertebrate communities that live in these streams.

Methods

Site selection

Sites were selected to represent a gradient of development, from high-intensity urban to forested reference (Table 1). Sites with both urban and agricultural activities in the watershed are categorized as “mixed” land use. Streambed sediment and fish from 31 sites were analyzed for organic and metal contaminants. Benthic invertebrates from 24 sites were collected for analysis of community composition and structure, and physical habitat characteristics were recorded at each of these sites. For this overview paper, results from selected sites are presented.

Fish sampling

Fish were collected by using an electrofisher, throw-net, or seine. Species selection was based on availability. Poeciliidae (guppies and mollies) were the most commonly collected fish. Other fish included those that people might eat (bass and tilapia), aquarium introductions (such as cichlids), and one sample of the native eleotrid (*Eleotris sandwicensis*). At 6 sites, more than one species was collected (to compare among species). At four sites, samples were collected in two different years (to compare between years). Composite samples of approximately 100 grams of whole fish of the same species (for organochlorine compounds) or 10 grams (for metals analysis) were obtained at each site. For smaller species, composites consisted of approximately 100 individuals. For larger species, five to eight individuals were composited.

Sediment sampling

Sediment samples were collected from undisturbed depositional zones along a 100-meter reach at each site. Sampling was confined to the upper 2 cm of bed sediment that represents contaminants most recently contributed to the stream (Shelton & Capel, 1994). Subsamples from along the reach were composited and wet-sieved in the field, using a 2-mm stainless steel sieve for the organics and a 63-µm sieve for metals. Samples were frozen on site and shipped to the laboratory for analysis.

Organic and metal analysis

Methods for processing sediment and fish followed nationally consistent procedures (Shelton & Capel, 1994; Crawford & Luoma, 1993), and all samples were analyzed at the U.S. Geological Survey National Water-Quality Laboratory in Denver, Colorado. Thirty-two organochlorine compounds and 43 metals were analyzed in streambed sediment. Twenty-eight organochlorine compounds were analyzed in fish tissue (Table 2). A list of constituents analyzed is available at: http://ca.water.usgs.gov/pnsp/pest.rep/bs-t.html.

Guidelines

Guidelines have been established for certain contaminants to help determine what concentrations of chemicals are likely to be associated with adverse biological effects. Concentrations measured in this study were compared with the Canadian Sediment Quality Guidelines (CSQG) for the protection of aquatic life (http://www.ec.gc.ca/ceqg-rcqe). Two assessment values have been calculated for the CSQG. The lower value of ISQG (interim sediment quality guideline) represents the concentration below which adverse effects to aquatic biota are rarely expected to occur. The upper value or PEL (probable effect level) defines the level above which adverse effects to aquatic biota are expected to occur frequently. These guidelines are based on chronic (long-term) effects of contaminants to aquatic organisms. Limitations of guidelines are that they have been established for only a limited number of pesticides and metals; the toxicity of mixtures and breakdown products is not generally considered; and sublethal effects, such as endocrine disruption, typically have not been assessed.

Benthic invertebrate sampling

Invertebrate samples were collected at each site by using a modified Surber-sampler (with a 425-mm mesh net) for quantitative riffle samples and a D-frame net (with a 210-mm mesh net) for qualitative multi-habitat samples (Cuffney *et al.*, 1993). All sampling was conducted during base-flow conditions. Quantitative samples provide estimates of organism relative abundance to allow comparison between sites. Qualitative samples were collected from all available habitats within the reach at each site to provide a comprehensive species list.

Invertebrate samples were identified and enumerated at the U.S. Geological Survey National Water-Quality Laboratory Biological Unit (Denver, Colorado) or by EcoAnalysts, Inc. in Moscow, Idaho. Verification of problematic taxa and routine quality-assurance checks on taxonomic identification were done by nationally recognized experts. Data reported for the quantitative samples include both species occurrence and density using numeric (300-fixed count) and time (total sorting time) criteria (Moulton *et al.*, 2000). Qualitative samples were analyzed only for species occurrence, by using a timed visual-sort method (Moulton *et al.*, 2000).

Habitat measurements

Habitat characteristics were determined at multiple spatial scales: basin, segment, reach, transect, and point (as described in: Fitzpatrick *et al.*, 1998; Brasher *et al.*, 2004). Basin and segment characteristics (watershed-scale features) such as land use, drainage area, and gradient were determined by using Geographic Information Systems (GIS) and topographic maps. Reach length at each site was determined as the linear distance equal to 20 times the average wetted channel width, with a minimum length of 100 meters. Within each reach, 11 equally spaced transects were established across the stream perpendicular to the direction of flow. Physical measurements of bank and riparian features and instream characteristics were made at each transect. Bank and riparian features included measurements such as bank angle, amount of erosion, and canopy cover. Instream habitat measurements included features such as aspect, wetted perimeter, depth, velocity, and substrate size. Point (microhabitat) measurements of depth and velocity were also made at each location where a quantitative invertebrate sample was collected. Water temperature (°C) was continuously recorded, using temperature loggers, at 30-minute intervals for approximately a 15-month period at 10 of the sampling sites.

Results and Discussion

Traditionally, water-quality monitoring has focused on water-column sampling. There are a number of reasons why it is important to analyze streambed sediment and fish for contaminants as well. Different types of compounds, including the organochlorine pesticides and metals, are more readily detected in sediment and tissue than in water because of their hydrophobic characteristics (they have low solubility in water but preferentially distribute into soil organic carbon and fatty tissues). Sediment serves as both a source and a removal mechanism for contaminants to and from the stream, and as a means of contaminant transfer downstream. Sediment also provides habitat for benthic biota and can be ingested by them. Aquatic biota are important in the food web around the stream, and some organisms such as fish are consumed by people and birds. In addition, fish and sediment can provide an integrated picture of contaminants over time.

The organochlorine pesticides most frequently detected at elevated concentrations in Hawaiian stream sediment and fish were dieldrin and chlordane (insecticides used for termite control) and DDT (an insecticide used in both agricultural and urban settings) and its derivative DDE (Fig. 2). Chlordane and aldrin (which breaks down into dieldrin) were used heavily in urban settings until discontinued in the mid-1980s (Takahashi, 1982). Despite the fact that they have not been used in almost 20 years, chlordane and dieldrin were prevalent in sediment and fish from urban watersheds, and concentrations consistently exceeded aquatic-life guidelines.

DDT was used to control agricultural pests in Hawai‘i and also was sprayed widely for mosquito control in urban areas (Robert Boesch, Hawai‘i Department of Agriculture, oral communication). Although DDT was banned in 1972, DDT and its derivatives (DDD and DDE) were prevalent in streambed sediment and fish from urban, agricultural, and mixed (urban and agricultural) watersheds. As with the organochlorine pesticides, the continued persistence of the DDT compounds in the environment likely reflects slow breakdown of the compounds, persistence in soils, and continual delivery to streams.

Following a trend that has been observed across the country (Schmitt *et al.*, 1990, 1999; Nowell *et al.*, 1999; Wong *et al.*, 2000), concentrations of organochlorine compounds are generally decreasing in Hawaiian streams (Brasher & Wolff, 2004). As part of the National Pesticide Monitoring Program, the U.S. Fish and Wildlife Service periodically analyzed organochlorine pesticides in fish from streams across the country, including two streams on O‘ahu; Waikele Stream and Mānoa Stream. In Waikele Stream, dieldrin, chlordane, and total DDT concentrations have decreased substantially since the 1970s. In Mānoa Stream, total DDT concentrations have decreased substantially but dieldrin and chlordane do not appear to have decreased much, if at all (Brasher & Wolff, 2004).

Concentrations of a number of trace elements and metals were elevated in streambed sediment samples (Fig. 3) at concentrations exceeding aquatic-life guidelines. These include arsenic, lead, and zinc, which are associated with anthropogenic activities, and others such as chromium and copper that naturally occur at high concentrations in Hawaiian rocks and soils (Anthony *et al.*, 2004). Concentrations of arsenic were highest in streams from agricultural and mixed (agricultural and urban) watersheds. Arsenic is a common impurity in fertilizer, and this may be the source of arsenic in these areas (Anthony *et al.*, 2004). Concentrations of metals associated with anthropogenic activities typically exceeded guidelines in developed (urban and agricultural) watersheds while those that naturally occur in Hawaiian rocks and soils (such as chromium) were elevated in forested areas as well.

Concentrations of organic contaminants tended to be higher in fish tissue than in associated streambed sediment (Brasher & Wolff, 2004). Concentrations of a number of the compounds analyzed for in Hawaiian streams were among the highest in the nation (Brasher & Wolff, 2004; Anthony *et al.*, 2004). Replicate samples of sediment and fish collected over 2 years, and among species at a site over 1 year substantiate these findings. Two or three different fish species were sampled at six different sites for organochlorine compounds. Three examples are shown in Fig. 4. In general, if a compound was detected in one of the species, it was detected in the other (Fig. 4). Concentrations between species for a given compound were very similar.

The same species were sampled during two different years at four different sites; three examples are shown in Fig. 5. In general, if a compound was detected in 1998 it was also detected in 2000

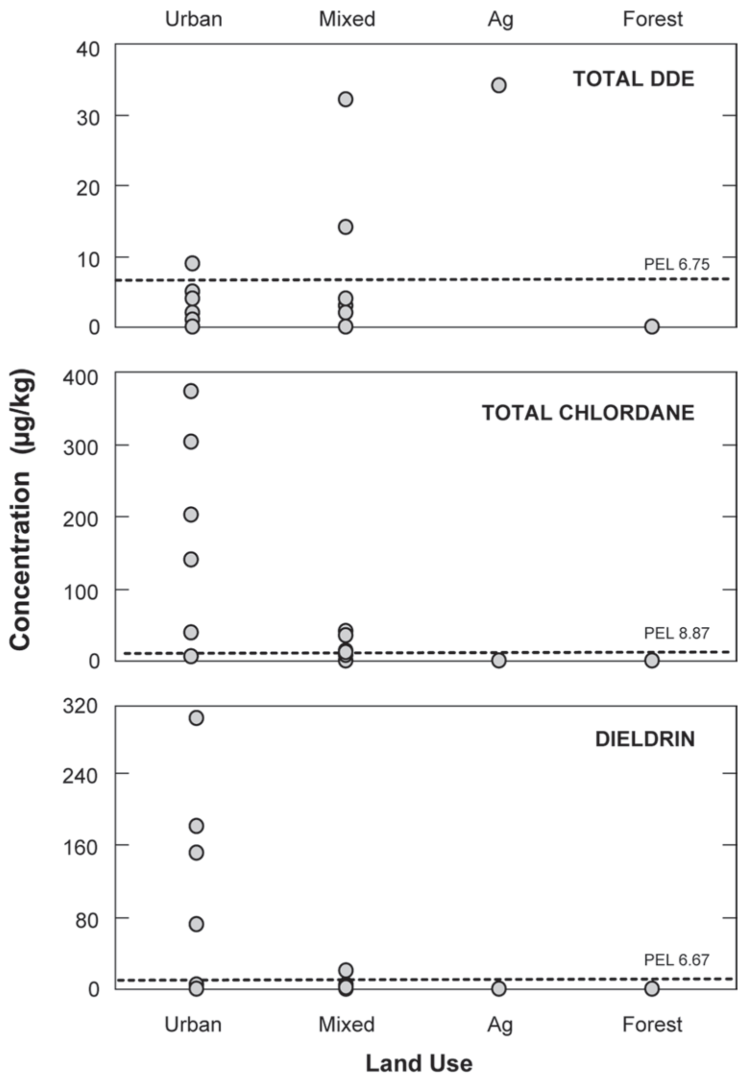

Figure 2. DDE (a breakdown product of DDT), chlordane, and dieldrin concentrations in sediment. Sites grouped by land use (Ag= agriculture). Sediment values are dry weight, concentrations in micrograms per kilogram (µg/kg). Canadian Sediment Quality Guidelines; PEL= probable effect level.

(Fig. 5). At two urban sites (KANE* and NUUA), concentrations of organochlorine compounds were very similar between years, and at a site in a forested watershed (WHEE), no organic compounds were detected either year.

A Principal Components Analysis (PCA) of organic contaminants and metals analyzed in sediment at 17 sites (where both organics and metals were analyzed) shows that the sites group together based on the type of contaminants that occur there, and that this grouping is associated with land use in the watershed (Fig. 6). Sites located in urban areas are characterized by the pesticides chlordane and dieldrin, PCBs, lead, cadmium, and zinc. Sites in agricultural and mixed (agricultural and urban) watersheds had elevated concentrations of DDT, and a number of metals including arsenic,

* see Table 1 for explanation of codes used for sites referred to in this paper.

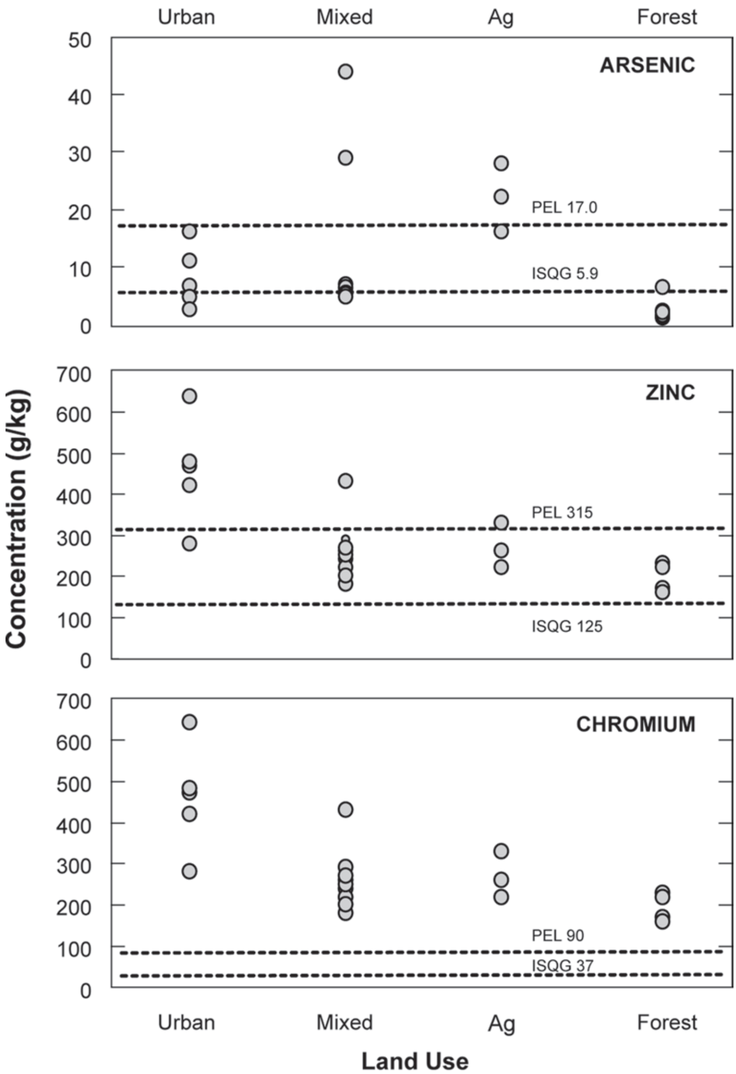

Figure 3. Arsenic, zinc, and chromium concentrations in sediment. Sites grouped by land use (Ag= agriculture). Sediment values are dry weight, concentrations in grams per kilogram (g/kg). Canadian Sediment Quality Guidelines; PEL= probable effect level, ISQG= interim sediment quality guidelines.

copper and mercury. Sites in forested areas had no detectable organic contaminants.

Many organochlorine pesticides and metals are known animal carcinogens and are potential human carcinogens. The adverse effects of DDT on reproduction in birds have been well documented, and other organochlorine pesticides have been linked to endocrine disruption, an alteration of natural hormonal activity (Kavlock *et al.*, 1996). These effects, combined with a slow rate of breakdown, make many organic and metal contaminants a long-term environmental concern. Endangered native waterbirds, such as the Hawaiian Stilt (*Himantopus mexicanus knudseni*), that consume fish or aquatic invertebrates may be at risk because of the elevated concentrations of these compounds in many Hawaiian streams.

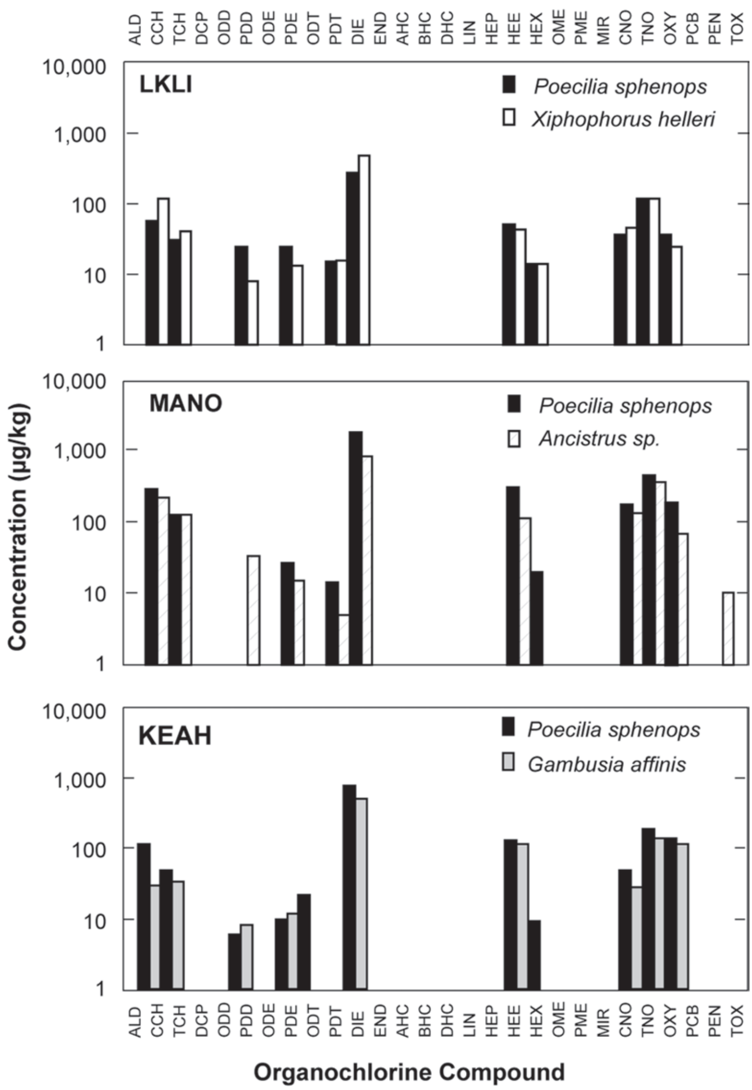

Figure 4. Comparison of organochlorine compound concentrations (Y axis is log scale) in different fish species collected at the same site. Tissue values are wet weight, concentrations in micrograms per kilogram (µg/kg). Site acronyms in Table 1. Acronyms for organochlorine compounds in Table 2.

Development is associated not only with changes in water quality but also with changes in physical habitat characteristics (Brasher, 2003; Brasher *et al.*, 2004). A PCA of physical habitat characteristics at the sampling sites indicates that the sites group together based on the type of anthropogenic activity in the watershed (Fig. 7). Sites in the lower left quadrant tended to be forested sites, with large substrate, natural channels, and low levels of silt. Sites in the lower right quadrant were urban sites with cement-lined channels, high levels of solar radiation, and silt. Sites in the upper right quadrant were agricultural sites, which tend to be channelized, with small substrate, but with more riparian cover than urban sites. Mixed sites, in the upper left quadrant, were similar to agricultural

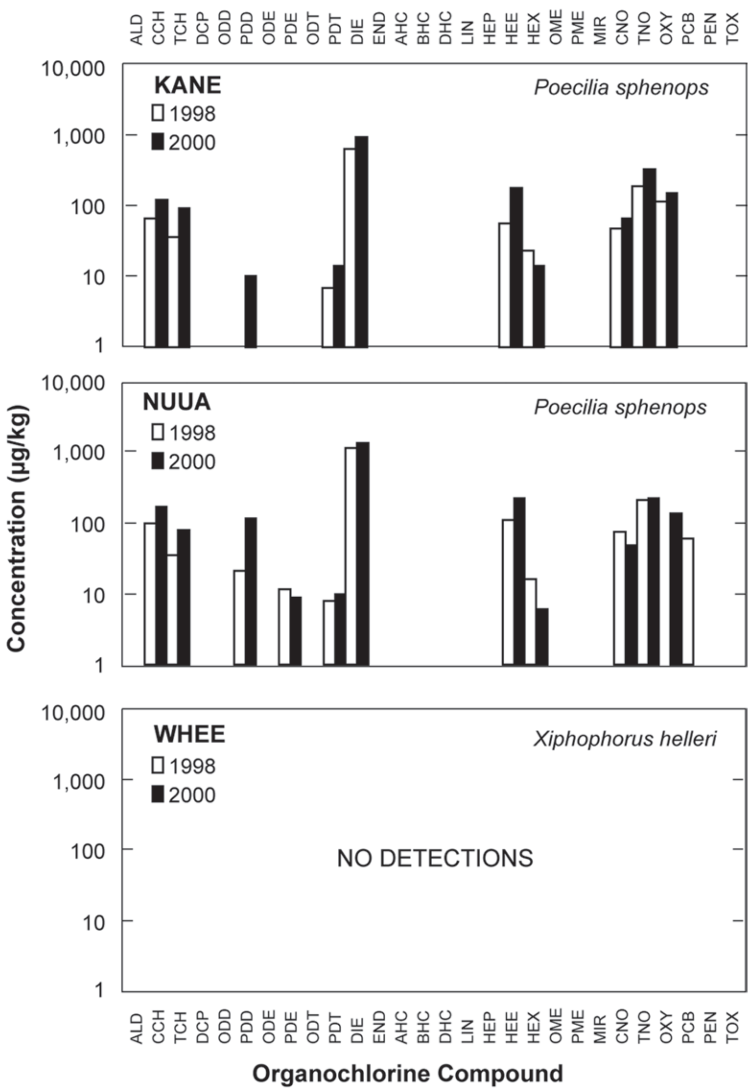

Figure 5. Comparison of organochlorine compound concentrations (Y axis is log scale) in fish collected in two different years. Tissue values are wet weight, concentrations in micrograms per kilogram (µg/kg). Site acronyms in Table 1. Acronyms for organochlorine compounds in Table 2.

sites in terms of higher levels of riparian cover (and consequently lower levels of solar radiation), to forested sites in terms of larger substrates, and they tended to lack the channel modification of urban and agricultural sites.

Overall, habitat characteristics of streams in urban and mixed (urban and agriculture) watersheds were markedly different from those in forested watersheds (Brasher *et al.*, 2004). Artificially straightened reaches with concrete-lined, flat-bottomed channels and reinforced banks are common in urban areas of Hawai'i. Such modifications are often accompanied by the removal of riparian vegetative cover and a reduction in substrate heterogeneity (removal of large boulders). The end result is a wide, shallow, unshaded, and generally homogeneous stream reach; a stark contrast to the steep,

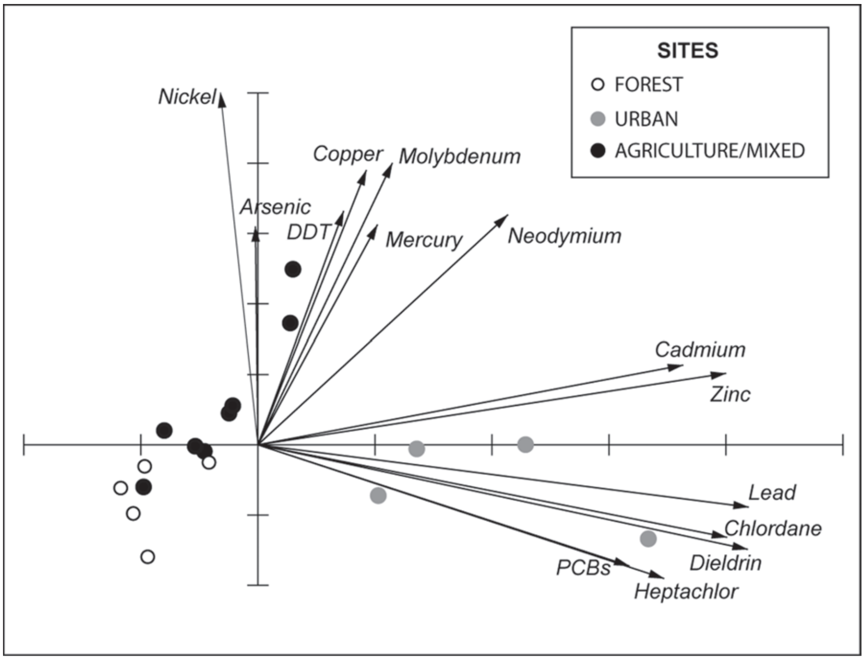

Figure 6. Principal Components Analysis of organochlorine pesticides and metals.

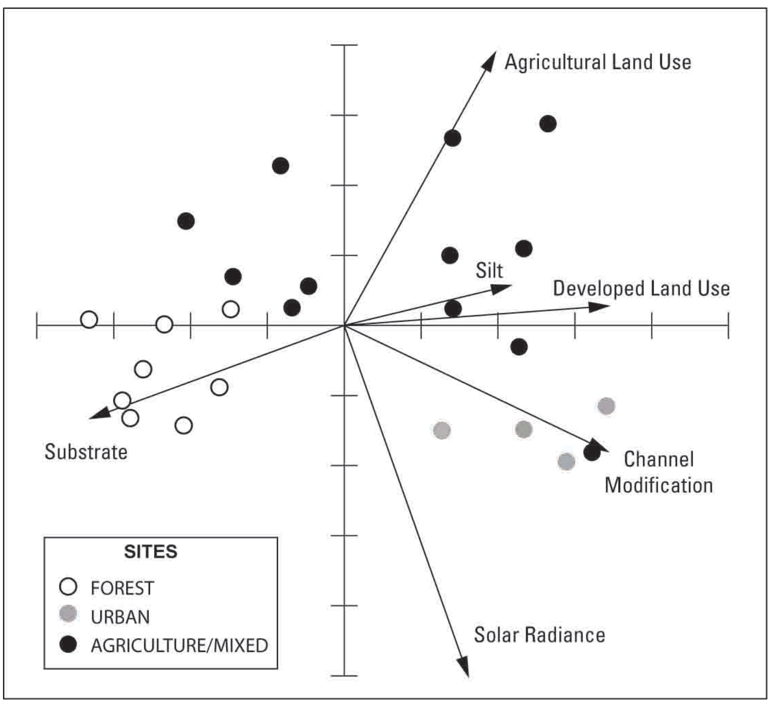

Figure 7. Principal Components Analysis of habitat variables.

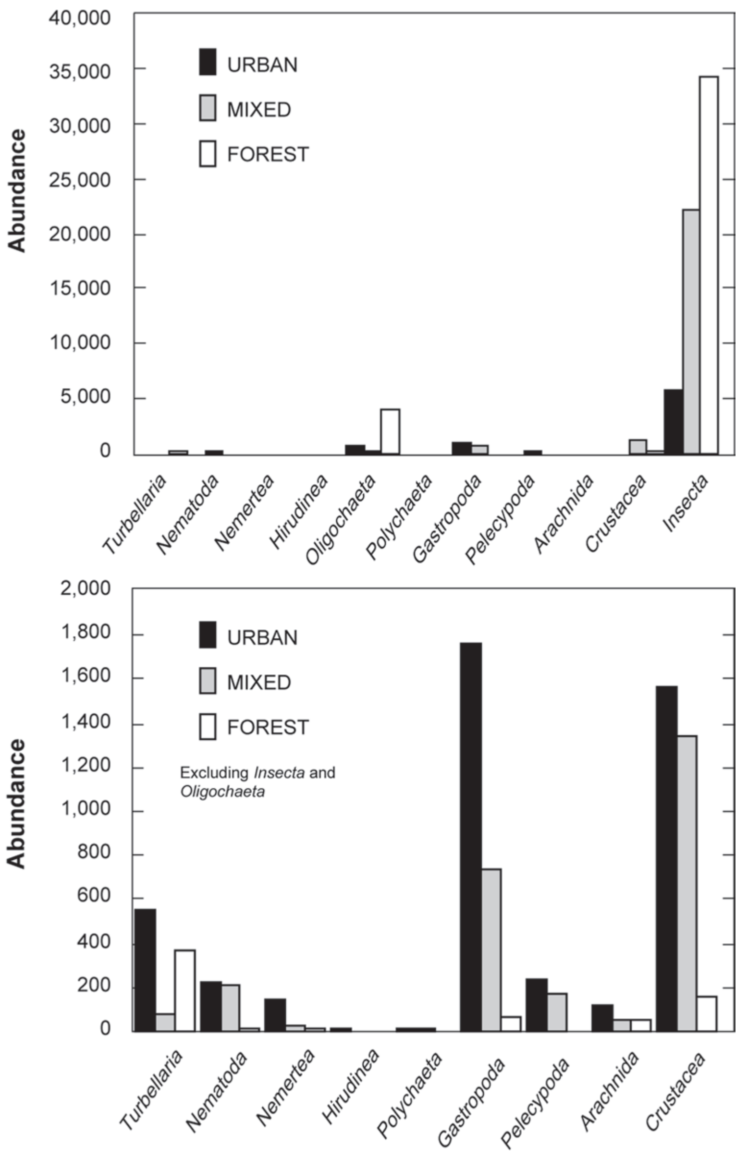

Figure 8. Invertebrate abundance (number of individuals) for selected classes. The top graph includes Insecta and Oligochaeta. Because of the high abundance in these two classes, the bottom figure excludes them, allowing for comparison among less abundant classes.

heavily vegetated, boulder-strewn reaches typical of more pristine streams in forested watersheds of Hawai‘i (Brasher *et al.*, 2004).

One effect of physical habitat alteration associated with channelization is a large increase in mean daily temperature and maximum temperature, as well as substantially greater temperature fluctuations (Brasher, 2003). Continuous water temperature probes located at 10 sites representing a gradient of watershed development indicated that streams at urban sites, which tended to be shallow and have reduced riparian cover, had much higher temperatures than forested sites (Brasher *et al.*, 2004).

Benthic invertebrate community structure likely reflects both the physical and chemical quality of the stream. Species composition and abundance were very different in developed versus undeveloped watersheds (Fig. 8). Most notably, insects accounted for a much larger proportion of the benthic invertebrate abundance in undeveloped (forested) watersheds than in developed (urban, and mixed urban and agricultural) watersheds. Although oligochaetes were associated with forested watersheds in the analysis, the abundance of oligochaetes was the result of a single forested site that periodically goes dry and consequently, has physical habitat characteristics more similar to developed watersheds (such as high levels of silt) where oligochaetes typically occur (Brasher *et al.*, 2004).

In an analysis of ten of the sites on O‘ahu, insects were determined to typically make up more than 80% of the invertebrate species in forested watersheds; introduced Trichoptera (caddisflies) were the dominant insect (Brasher, 2003). In contrast, insects typically made up only about half of the invertebrates at urban sites, with Diptera (true flies) more abundant than caddisflies (Brasher, 2003). A similar pattern has been documented in New Zealand, where a more pristine site was dominated by mayflies and caddisflies and a more developed site was dominated by true flies (Death, 2000).

Urban sites had the lowest abundance of insects and high numbers of gastropods and crustaceans (Fig. 8). No native gastropods were collected during this study. The most abundant gastropods were the pan-tropical thiarid snails, the introduced clam (*Corbicula fluminea*), and a limpet (*Ferrissia sharpi*). Gastropods occurred almost exclusively at channelized sites (Brasher *et al.*, 2004). As has been reported in Japan (Karr & Chu, 1997), the most common gastropods present in developed areas of Hawaii are nonnative and indicators of degraded conditions. Crustaceans collected from streams in forested watersheds tended to be either the native atyid shrimp (*Atyoida bisulcata*) or the widespread introduced Tahitian prawn (*Macrobrachium lar*). The dominant crustaceans at developed sites were the introduced crayfish (*Procambarus clarkii*), and the introduced atyid shrimp (*Neocaridina denticulata*).

Conclusions

Elevated concentrations of pesticides used for termite control (dieldrin and chlordane) and DDT were measured in sediment and fish from streams in developed watersheds. These concentrations often greatly exceeded guidelines for the protection of aquatic species. Metals associated with anthropogenic activities (such as lead, zinc, and arsenic) were measured in sediment from developed watersheds at concentrations that exceeded aquatic-life guidelines. Concentrations of some metals (such as chromium and copper) are naturally high in Hawaiian soil and rocks and were measured at concentrations exceeding guidelines even in forested areas.

Water-quality degradation and physical habitat alteration tend to co-occur in developed watersheds. Ongoing analysis is being conducted to further elucidate the relative contribution of these two factors to stream quality and to the integrity of benthic macroinvertebrate communities in Hawaiian streams. In addition, an understanding of associations between anthropogenic activities and the resulting introduction of organic and metal contaminants into aquatic systems will allow land-management practices to be designed to reduce the loading of contaminants to streams and nearshore waters.

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