



Use of hydroacoustic measurements to characterize bottom sediments and guide sampling and remediation of organic contaminants in lake sediments

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HIGHLIGHTS

- Hydroacoustic measurements provide information about sediment distribution in lakes.
- Sediment distribution can serve as guide for sampling and remediation.
- Chemical analyses identify sediments with elevated concentrations of contaminants.

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ABSTRACT

Sampling of bed sediment for contamination characterization is often limited by the heterogeneity in sediment properties and distribution. In this study, we explored the use of hydroacoustic measurements to characterize sediment properties and guide sediment sampling in a small lake contaminated by organochlorine pesticides (OCPs) and PCBs. A dual frequency hydroacoustic survey was conducted to characterize sediment properties, distribution, and thickness in McGrath Lake, near Ventura, CA. Based upon these results, sediment core samples were collected from 15 sites on the lake, and sectioned into 20 cm intervals for sediment characterization and analysis of OCPs and PCBs. Very high concentrations of total DDT and total chlordane were found in the sediments, with mean values of 919 and 34.9 ng g⁻¹, respectively. Concentrations of OCPs were highest at 60–80 cm depth near the inflow at the north end of the lake. Total PCB concentrations were much lower (mean concentration of 4.5 ng g⁻¹). Using the hydroacoustic and chemical data, it was estimated that nearly 30,000 m³ of DDT- and chlordane-contaminated sediment (above effects range median values) was present in the uppermost 1.2 m of sediment in the lake. A hydroacoustic survey can be a valuable tool used to delineate sediment distribution in a lake, identify areas with deeper organic sediment where hydrophobic contaminants would likely be found, and guide sampling. Sampling and chemical analyses are nonetheless needed to quantify contaminant levels in bottom sediments. When combined with hydroacoustic measurements, this approach can reasonably estimate the distributions and volumes of contaminated sediment important in the development of remediation strategies.

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1. Introduction

Bed sediment is the repository of many legacy and contemporary contaminants, including heavy metals and hydrophobic organic pollutants such as PCBs and DDT. Once in sediment, these contaminants may pose risks to benthic organisms or humans through food chain exposure, or become secondary contamination sources if resuspension or off-site transport occurs. Sediments in surface water bodies such as lakes are often highly heterogeneous within lake basins, however, with sediment properties varying significantly as a result of differential fluvial inputs, wind resuspension, sediment focusing, littoral zone production, and other processes (Downing

and Rath, 1988; Hakanson and Jansson, 2002). At the same time, sampling and analysis of sediments are generally time-intensive and expensive; as a result, a limited number of samples are typically collected. The collection of a finite number of sediment samples on a regular or random grid is thus generally insufficient to fully capture the heterogeneity in sediment properties, thickness and level of contamination.

Understanding the sediment properties in advance of sampling allows for more efficient and optimized sampling. Hydroacoustic measurements can rapidly collect georeferenced data about lake depth (Lurton, 2002), sediment properties (e.g., organic C content, water content) (Anderson and Pacheco, 2011; Tegowski, 2005), and sediment thickness (Odhambo and Boss, 2004; Dunbar et al., 1999) at thousands to millions of sites on a lake. Hydroacoustic measurements of lake bathymetry, sediment properties and sediment thickness thus provide key information that can be used for optimized sampling of

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sediments, and also allow more accurate spatial extrapolation of discrete sediment sampling results and estimation of volumes of contaminated sediments.

The objective of this study was to explore the use of hydroacoustic measurements in conjunction with core sampling and chemical analysis of hydrophobic pollutants for bed sediment characterization. McGrath Lake (Ventura, CA) was selected for study. McGrath Lake is contaminated with a range of organochlorine pesticides and PCBs due to historical loading of the contaminants via surface runoff and drainage from the surrounding agricultural lands and other sources in the watershed.

2. Materials and methods

2.1. Study site

McGrath Lake is a small (approximately 0.05 km²) back-dune lake located near Ventura, CA. The lake is situated adjacent to the Pacific Ocean at 34.212°N, –119.254°W, and receives water from agricultural runoff and drainage, groundwater and direct precipitation. The lake is brackish, with a salinity of 2.3 ppt on the date of sediment core sampling.

Samples collected in the late 1990s documented some of the highest sediment concentrations of organochlorine (OC) pesticides and PCBs in the State of California (Jacobi et al., 1999). As a result, McGrath Lake was identified under the Statewide Bay Protection and Toxic Cleanup Program (BPTCP) as a high priority toxic “hot spot”.

2.2. Hydroacoustic measurements

As the initial phase of this study, a hydroacoustic survey of bathymetry and bottom sediment properties was conducted on December 8, 2011. Measurements were made from a 12' Sea Eagle inflatable catamaran with a 2.5 HP 4-stroke outboard using a BioSonics DTX echosounder along a series of transects, with position recorded using a JRC 212W real-time differential GPS receiver. Measurements were made with BioSonics 430-kHz and 38-kHz single beam transducers with integrated pitch-roll sensors at 5 pings per second and pulse length of 0.4 ms. Example echograms from the survey are provided in Fig. 1, showing volume backscatter strength (Sv) at 38- and 430-kHz for a site with a 79 cm thick organic sediment overlaying a dunal sand substrate. The intensity of acoustic backscatter from an object is a complex function of frequency, density contrast with water, and size and shape of the object. One notes that bottom sediments represent the dominant source of acoustic backscatter (e.g., Fig. 1), although many objects in water can produce backscatter, including fish (Simmonds and MacLennan, 2006), zooplankton (Hembre and Megard, 2003) and submerged aquatic vegetation (Winfield et al., 2007).

Water column depth was measured across the lake from echograms recorded at 430-kHz based upon transducer depth, known speed of sound and the time delay between the transmitted soundwave and the bottom echo return. The 430-kHz transducer has a short near-field and high absorption by sediments, providing a sensitive acoustic response to small density contrasts with water as found in soft surficial organic sediments with high water contents. The sharp increase in backscatter strength at range (distance below transducer face) of approximately 1.6 m in Fig. 1 represents the sediment–water interface at this site. Water column depths were extracted from echograms using the bottom-detection algorithm in Sonar5 Pro (Balk and Lindem, 2009).

The bottom echo envelope (i.e., the time-dependent amplitude of a received pulse) also holds information about the properties (Tegowski, 2005; Anderson and Pacheco, 2011) and thickness of bottom sediments (Dunbar et al., 1999). One notes that backscatter strength at 430-kHz increased sharply to about –25 dB, yielded strong backscatter for relatively short distance in the sediments,

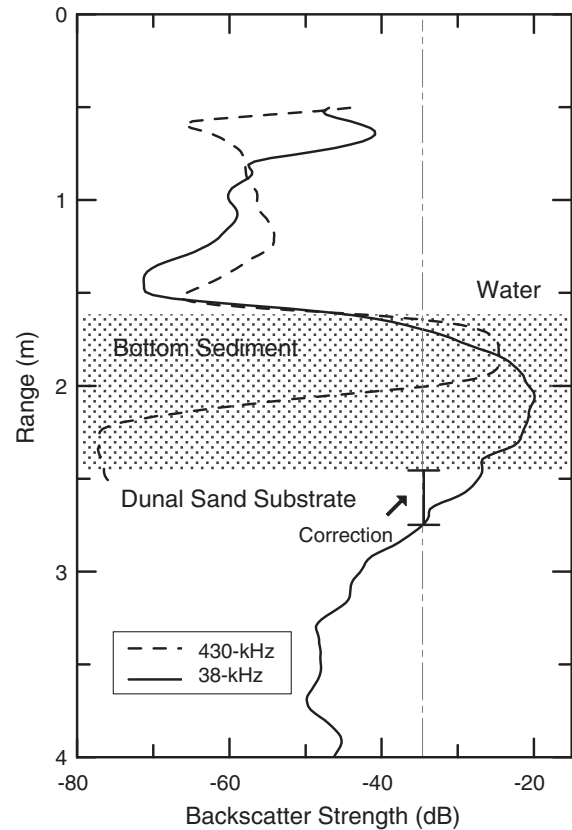


Fig. 1. Example echograms showing volume backscatter strength as function of range from transducer face at 38- and 430-kHz at site with 79 cm sediment layer (measured through coring).

and then was attenuated quite rapidly at greater range (below about 2 m) (Fig. 1). The intensity and shape of the bottom echo envelope, including the increasing (first) part of the first bottom echo (E1'), decreasing (second) part of the first bottom echo (E1), and fractal dimension have previously been shown to provide information about properties of bottom sediments. The E1' has been used as an indication of bottom hardness, while E1 provides a measure of bottom roughness and volume backscatter (Ostrovsky and Tegowski, 2010). Echograms were analyzed for attributes of the bottom echo envelope (E1', E1 and fractal dimension) using BioSonics Visual Bottom Typer with a 10 ping averaging window (BioSonics Inc., 2008).

The thickness of the sediments was determined from the difference between the water column depth measured at 430-kHz (described above) and the range to the back edge of the bottom echo at 38-kHz (Dunbar et al., 1999) (Fig. 1). The 38-kHz transducer was used to estimate sediment thickness due to its weak absorption by water and organic-rich sediments (Lurton, 2002), thus allowing penetration into and backscatter from sediments until a relatively dense substrate with stronger absorption was encountered (in this case, the dunal sand substrate). Measurements at shallow sites with exposed dunal sand yielded relatively rapid attenuation in backscatter strength, to less than –35 dB within approximately 20–30 cm; as a result, a thickness correction of 0.25 m was applied for backscatter from penetration of the soundwave into the dunal sand substrate with a –35 dB cutoff (Fig. 1).

2.3. Sediment sampling

An initial set of surface sediment grab samples were collected during the hydroacoustic survey using an Ekman dredge at 5 sites on the lake. Surface grab samples were homogenized and subsampled into individual 500-mL wide-mouth glass jars with Teflon-lined lids. Samples were stored on ice in a cooler and returned to the laboratory for analysis.

Following the processing and analysis of the hydroacoustic data, intact sediment cores were collected from 15 sites using an Aquatics Instruments universal percussion corer with thin-walled clear polycarbonate core barrels (68 mm × 71 mm × 120 cm) and alum extension handles. Sediment cores were extruded into 20 cm sections, homogenized and subsampled into new 500-mL wide-mouth glass jars with Teflon-lined lids and stored on ice until returned to the laboratory. Samples were maintained in a 4 °C cold room and homogenized prior to analyses that typically began within a few days following the sample collection.

2.4. Sediment analysis

2.4.1. Basic sediment characterization

Water content was determined on subsamples that were dried overnight at 105 °C. Total C and N were measured by dry-combustion methods using a Thermo Flash EA N/C soil analyzer (Nelson and Sommers, 1982). Inorganic C and CaCO₃ were determined manometrically following Loeppert and Suarez (1996), with organic C taken as the difference between total C and inorganic C. Duplicate analyses were conducted at a rate of at least one every 10 samples within an analytical batch.

2.4.2. Extraction and analysis for organochlorine pesticides and PCBs

Organic contaminants were extracted after the sediment samples were homogenized, freeze-dried and ground using a mortar and pestle. All samples were extracted using a Dionex (Sunnyvale, CA) ASE 350 accelerated solvent extraction (ASE) system. Pre-combusted Ottawa sand (0.5 g, Fisher Scientific) was placed in the bottom of each extraction cell, followed by 5.0 g of a freeze-dried sediment. The sediment was spiked with 50 ng of each surrogate (PCB 65 and PCB 209) dissolved in hexane, allowed to evaporate before being capped with sand and sealing the cell. Samples were then extracted over 3 cycles at 100 °C and 1500 psi for 5 min with methylene chloride. The extracts were dried using nitrogen gas and immediately 1.0 mL hexane was added along with 2 g of activated copper to remove elemental sulfur. Samples were allowed to set for 10 min with copper prior to cleanup to ensure sufficient sulfur removal.

Solid phase extraction with Florisil cartridges (Fisher Scientific) was used to clean up sample extracts. Fisher PrepSep R Florisil (1 g) cartridges were first conditioned using 5 mL of hexane. Samples were transferred to the cartridge and the eluent was captured in a 15 mL collection vial. The target compounds were eluted from the cartridge using 3 mL of hexane:acetone (9:1, v/v) followed by 7 mL of hexane. The eluent was evaporated to dryness under a stream of nitrogen gas and immediately redissolved in 0.5 mL of hexane before being transferred to a GC vial. Internal standards (PCB 30, PCB 205 and ¹³C cis-permethrin) were added to each vial and the final volume was brought to 1.0 mL before sealing the vial.

Extracts were analyzed using a Varian CP-3800 GC coupled with a 1200 Quadrupole MS/MS and a DB-5 MS column (30 m × 0.25 mm × 0.25 μm) (J&W Scientific, Folsom, CA). The triple-quadrupole was operated in electron ionization (EI) mode using selective ion monitoring (SIM). Each compound and its analytical parameters are listed in Table 1. The following analytical procedure was adapted from Bay et al. (2003) and Fernandez et al. (2012). The column oven temperature ramp was as follows: initial temperature 80 °C, held for 1 min, increased to 200 °C at a rate of 10 °C min⁻¹ before increasing to 300 °C at a rate of 5 °C min⁻¹ and then finally held for 5 min. The total run time was 38 min. A standard curve was run for PCBs (6 points, 0.5 to 100 ppb) and OCPs (9 points, 0.5 to 5000 ppb) prior to and after the analysis. The r² of each analyte standard curve was above 0.995. The analysis of OCPs required a broader standard curve range than PCBs due to their higher concentrations. Duplicates, 50 ng matrix spikes and matrix spike duplicates (matrix spikes were only run for PCBs due to the high concentration of organochlorine pesticides) were similarly extracted, cleaned and

Table 1

Mass spectrometry detection conditions of PCBs, organochlorine pesticides and their surrogates and internal standards.

Column elution order	Retention time (min)	Compound	Precursor ion (m/z)	Product ion (m/z)	Collision energy (eV)	LOD (ng g ⁻¹)	LOQ (ng g ⁻¹)
<i>PCBs</i>							
2	11.529	PCB 18	256	186	35	0.1	0.3
3	13.026	PCB 28	256	186	35	0.1	0.3
4	14.21	PCB 52	292	220	35	0.1	0.3
5	14.234	PCB 49	292	220	35	0.1	0.3
7	14.736	PCB 44	292	220	35	0.1	0.3
8	14.955	PCB 37	256	186	35	0.1	0.3
9	15.965	PCB 74	292	220	35	0.1	0.3
10	16.123	PCB 70	292	220	35	0.1	0.3
11	16.189	PCB 66	292	220	35	0.1	0.3
14	16.988	PCB 101	326	254	35	0.1	0.3
15	17.129	PCB 99	326	254	35	0.1	0.3
17	17.309	PCB 119	326	254	35	0.1	0.3
18	17.899	PCB 87	326	254	35	0.1	0.5
19	17.903	PCB 81	292	220	35	0.1	0.3
22	18.162	PCB 110	326	254	35	0.1	0.3
23	18.266	PCB 77	292	220	35	0.1	0.4
24	18.546	PCB 151	360	290	30	0.1	0.3
26	18.97	PCB 149	360	290	30	0.1	0.4
27	19.005	PCB 123	326	254	35	0.1	0.5
28	19.115	PCB 118	326	254	35	0.1	0.2
29	19.852	PCB 153/168	360	290	30	0.1	0.3
30	19.964	PCB 105	326	254	35	0.1	0.5
32	20.786	PCB 138/158	360	290	30	0.1	0.3
33	21.126	PCB 126	326	254	35	0.1	0.3
34	21.261	PCB 187	394	324	35	0.1	0.3
35	21.45	PCB 183	394	324	35	0.1	0.3
36	21.641	PCB 128	360	290	30	0.1	0.3
37	21.771	PCB 167	360	290	30	0.1	0.3
38	22.226	PCB 177	394	324	35	0.1	0.3
39	22.507	PCB 156	360	290	35	0.1	0.3
40	22.589	PCB 200	430	358	35	0.1	0.3
41	22.663	PCB 157	360	390	35	0.1	0.3
42	23.068	PCB 180	394	324	35	0.1	0.3
43	23.814	PCB 169	360	290	35	0.1	0.3
44	23.994	PCB 170	394	324	35	0.1	0.3
45	24.245	PCB 201	430	358	35	0.1	0.4
46	25.023	PCB 189	394	324	33	0.1	0.3
48	26.152	PCB 194	430	358	35	0.1	0.3
50	27.307	PCB 206	464	392	36	0.1	0.3
<i>Organochlorine pesticides</i>							
12	16.817	t-Chlordane	372	264	20	0.1	0.5
13	16.866	o,p'-DDE	247	176	20	0.1	0.4
16	17.212	c-Chlordane	372	264	20	0.1	0.4
20	17.954	p,p'-DDE	247	176	20	0.1	0.7
21	18.159	o,p'-DDD	235	165	15	0.1	0.6
25	19.508	p,p'-DDD/o,p'-DDT	235	165	15	0.1	0.4
31	20.75	p,p'-DDT	235	199	10	0.2	1.0
<i>Surrogates</i>							
6	14.425	PCB 65	292	220	35	NA	NA
51	28.27	PCB 209	498	428	30	NA	NA
<i>Internal standards</i>							
1	11.162	PCB 30	256	186	35	NA	NA
47	25.902	¹⁴ C c-permethrin	189	174	12	NA	NA
49	26.293	PCB 205	430	358	35	NA	NA

NA = not applicable.

analyzed at a frequency of 1 per 10 samples. Surrogate spike recoveries across all samples averaged 90.4 ± 13.6% and PCB matrix spikes (corrected for unspiked concentrations) were 103 ± 14%. Relative percent differences (RPDs) between duplicates averaged 15.1 ± 7.5% for total DDT, 16.4 ± 13.6% for total chlordane, and 17.7 ± 13.8% for total PCBs. As an additional check on our analytical methods, two representative samples (specifically, site 7, 20–40 cm and site 3, 100–120 cm) were split and also analyzed by E.S. Babcock Laboratories in Riverside,

CA using method USEPA 8081A. A very good agreement was found between total DDT concentrations measured in our laboratory and that at the certified commercial laboratory (344.7 vs. 317.4 ng g⁻¹ for site 3; 545.1 vs 627.7 ng g⁻¹ for site 7, or RPDs of 8.2 and 14.1%, respectively). Total PCB and total chlordane concentrations in the sample splits were below the commercial laboratory's reportable detection limits of 900 ng g⁻¹ and 120 ng g⁻¹, respectively.

3. Results

3.1. Hydroacoustic results

Hydroacoustic measurements were used to quantify the bathymetry and spatial distribution of sediment thickness and properties in McGrath Lake. A bathymetric map of the lake was developed from depth measurements made at 39,892 points on the lake using Surfer (Golden Software) (Fig. 2a). McGrath Lake is a very shallow lake, with a mean depth of 1.2 m and maximum depth of only 2.6 m at the date of sampling (Table 2). Depth was found to increase from north to south, with depths <0.8 m in the northernmost part of the lake where inflows enter the lake (attributed to deposition of eroded soil from the watershed), to the maximum value (about 2.6 m) in a

small deeper hole at the very southern end (Fig. 2a). Total surface area of the lake was estimated at 0.049 km².

The acoustic backscatter at 430-kHz from bottom sediments was also used to estimate the distribution of organic carbon across the lake (Anderson and Pacheco, 2011). Regression of acoustical properties with the organic C content of surficial (top 10 cm) sediments collected with an Ekman dredge during preliminary sampling at the lake was correlated ($r^2 = 0.53$) with the first part of the bottom echo (E1'), where echo amplitude increased sharply (Anderson and Pacheco, 2011). This relationship was used to convert measured E1' values across the lake to estimated % organic C contents (Fig. 2b). Organic C contents ranged from <0.02% to almost 4%, with very shallow sediments (Fig. 2a) generally possessing negligible organic C (Fig. 2b). The highest organic C concentrations were found in a band in the north-central part of the basin (about 34.2130–34.2138 °N) although patchiness was evident in the acoustically-inferred organic C distribution (Fig. 2b).

Measurements of sediment thickness made using the 38-kHz transducer at known GPS coordinates across the lake were used to develop a contour map of corrected acoustically-derived sediment thickness (Fig. 2c). Sediment thickness varied across the lake, with very thin sediments near the lake margin and in a region in the southern part of the lake, while sediment thickness was generally 0.5–1 m

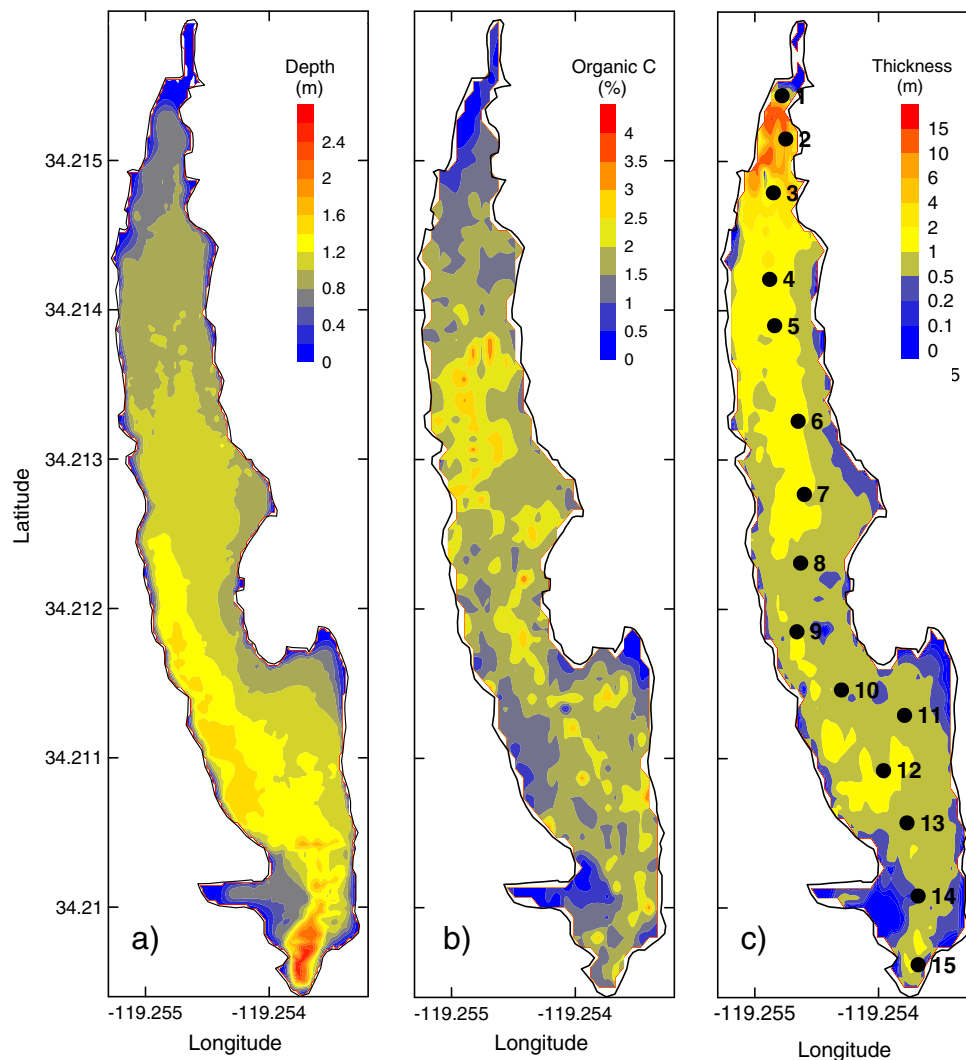


Fig. 2. Properties of McGrath Lake derived from hydroacoustic measurements: a) bathymetry, b) sediment organic C and c) sediment thickness and core sampling sites. (Echograms shown in Fig. 1 were taken at site 15.)

Table 2
Basin morphometry for McGrath Lake.

Attribute	Value
Mean depth (m)	1.2
Maximum depth (m)	2.6
Lake surface area (m ²)	49,070
Sediment volume (m ³)	52,815
Mean sediment thickness (m)	1.1

over most of the lake area (Fig. 2c). Much thicker sediments (potentially 10–15 m thick) were found in a small area at the northernmost end of the lake (Fig. 2c).

Using geospatial processing from data in Fig. 2c, the total sediment volume in the lake was estimated to be 52,810 m³. Based upon these values, the mean sediment thickness over the whole basin was estimated to be 1.1 m (Table 2). The majority of the sediment volume is located in the upper part of the sediment column. For example, 39,204 m³ (74.2%) of sediment was calculated to reside within the uppermost 1.2 m of the bottom sediments. Based upon bathymetry that generally showed increasing depth down the long axis of the lake (Fig. 2a), acoustically-inferred surficial organic C contents that not only exhibited greater heterogeneity but also exhibited gradients down the lake (Fig. 2b), and sediment thickness (Fig. 2c), 15 sites were selected for core sampling and analysis for OC pesticides and PCBs (Fig. 2c, solid circles).

3.2. Sediment properties

Measurements of basic sediment properties on 54 subsamples collected from the 15 core sampling sites indicate the average sediment water content to be 53.9% by weight, the average bulk density 0.65 g (dry-weight) cm⁻³, and the organic and inorganic C concentrations 2.14 and 2.89%, respectively (Table 3).

Organic C content was consistently highest in the sediment surface and decreased with depth; surface concentrations also generally increased longitudinally down the lake (Fig. 3). Water content was strongly correlated with organic C content ($r^2 = 0.75$) and also decreased with depth below the sediment surface, reflecting increased bulk density, consolidation and compaction in part due to sediment overburden pressure (data not shown).

3.3. Contaminant concentrations

3.3.1. DDT and derivatives

High concentrations of total DDT (taken as the sum of o,p-DDD, o,p-DDE, p,p-DDD, o,p-DDT, p,p-DDE and p,p-DDT) were present in the sediments (Table 4). Total DDT averaged 919 ng g⁻¹ in the sediment samples, and exceeded the effects range low (ERL) concentration (1.58 ng g⁻¹) in 54 (100%) samples, and exceeded the effects range median (ERM) concentration in 52 (96%) samples (Table 4). Concentrations below the ERL rarely elicit adverse effects, while those above the ERM regularly result in negative effects (Buchman, 1999).

p,p-DDE was the dominant form of DDT present in the sediments (Table 4), accounting for an average of 75% of the total DDT found. DDE is formed from dehydrochlorination of DDT under aerobic

conditions and is the most common form in historically contaminated soils and waters. The mean concentration of total DDE (p,p-DDE and o,p-DDE) was 644 ng g⁻¹ and greatly exceeded its ERL value of 2.2 ng g⁻¹ in all samples (Table 4). Total DDE concentrations also exceeded the ERM value of 27.0 ng g⁻¹ in all but 2 samples (Table 4). The sum of the DDD species (o,p-DDD and p,p-DDD) averaged 224.4 ng g⁻¹ in the core samples and exceeded the ERL for DDD (2 ng g⁻¹) in 100% of the samples analyzed as well, while the majority of samples (91%) also exceeded the ERM value of 20 ng g⁻¹ (Table 4). p,p-DDT was found in much lower concentrations in the sediments (mean value of 21.5 ng g⁻¹) relative to most of the other DDT species, but still exceeded its ERL and ERM values in 85% and 72% of samples. One should note that the ERL and ERM listed in Table 4 for DDT are based upon the sum of concentrations of both p,p'-DDT and o,p'-DDT. However, it was not possible to fully resolve o,p'-DDT from p,p'-DDD under the chromatographic conditions used here, therefore the mass recovered from this was assigned exclusively to p,p'-DDD, which should be the more dominant species due to DDT degradation over the last 40 years.

The concentration of total DDT (and DDE and DDD) varied vertically and down the long axis of the lake, with highest concentrations located at 60–80 cm depth at the north end (near the inflow) (Fig. 4a). Much lower concentrations were generally present near the central and southern sections of the lake, although levels did increase again somewhat in the small deeper region at the southernmost site (site #15) (Fig. 2). Consistently lower levels of total DDT were present in sediments at the interface with the dunal sand that forms the lake basin. Notwithstanding, it is clear that DDT and its degradation products that are more commonly found in contaminated sediments and waters are at levels that exceed, often by a very wide margin, ERL and ERM concentrations throughout McGrath Lake.

3.3.2. Total chlordane

Sediment samples were also analyzed for total chlordane concentrations (cis-chlordane and trans-chlordane). Sediment concentrations varied by 3 orders of magnitude (0.1–115.0 ng g⁻¹), with an average of 34.9 ng g⁻¹ (Table 4). Fifty-one samples (94%) were found with total chlordane levels above the ERL value of 0.5 ng g⁻¹, while almost one-half (48%) of samples exceeded the ERM value of 6.0 ng g⁻¹ (Table 4). The distribution of total chlordane (Fig. 4b) was similar to that found for total DDT (Fig. 4a), with maximum concentration present at 60–80 cm depth near the inflow to the lake, and lower concentrations above and below this depth and further into the basin.

3.3.3. Total PCBs

Unlike the OC pesticides, which were found at very high concentrations, levels of total PCBs were low; concentrations ranged from <0.1 to 18.7 ng g⁻¹ and averaged 4.5 ng g⁻¹ (Table 4). These values are all below the ERL of 22.7 ng g⁻¹ (Buchman, 1999) and so are not expected to present significant ecological concern. The distribution of total PCBs differed somewhat from that found for total DDT (Fig. 4a) and total chlordane (Fig. 4b), with highest concentrations found slightly deeper in the sediments and present a little further south into the lake (Fig. 4c).

3.3.4. Volumes of contaminated sediments

The hydroacoustic measurements provide important 3-dimensional information about sediment distribution within the basin (Fig. 2c). Assuming that the primary gradients in contaminant concentrations within the basin are in the vertical and longitudinal directions (i.e., with depth and down the long axis of the lake) (Fig. 4), we can develop volumetric estimates of contaminated sediments. We assumed that the concentrations were uniform in the short transverse direction (although thicknesses varied) based upon the results from linear regressions of organic C contents of sediments across three 65 m transects

Table 3
Basic properties of McGrath Lake sediments from cores up to 1.2 m depth sectioned into 20 cm sections (n = 54).

Property	Mean ± s.d.	Range
H ₂ O content (%)	53.9 ± 12.0	17.5–72.9
Bulk density (g cm ⁻³)	0.65 ± 0.21	0.35–1.27
Organic C (%)	2.14 ± 0.86	0.22–4.59
Inorganic C (%)	2.89 ± 1.62	0.36–6.49

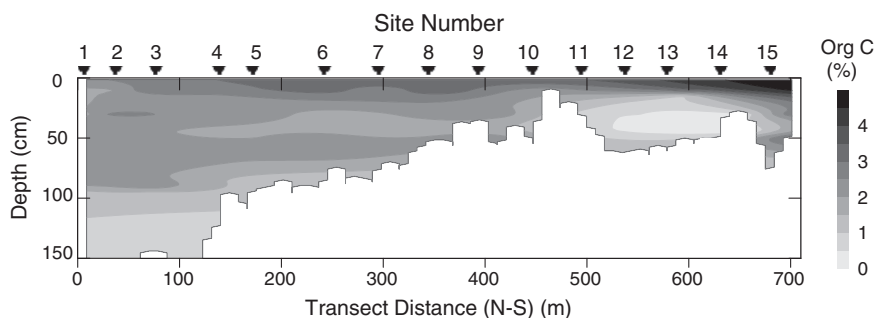


Fig. 3. Organic C concentrations in sediments of McGrath Lake (dry-weight basis).

each in the transverse and longitudinal directions near sites 3, 5 and 6 (Fig. 2). Linear regressions of organic C concentrations yielded no statistically significant gradients (slopes to regression line) for any of the transverse transects (average p -value of 0.407), while two out of the three longitudinal transects yielded strongly statistically significant gradients in organic C ($p = 0.002$ and 0.021), with an average p -value across the three longitudinal transects of 0.049. Gradients in organic C were thus present in the longitudinal direction, but absent in the transverse direction. Longitudinal gradients in sediment properties are often witnessed away from inflows (Hakanson and Jansson, 2002). Given the strong binding of hydrophobic contaminants to soil and sediment particles (Karickhoff et al., 1979) and the potential for sediment deposition near the inflow, gradients in pesticide concentrations would likely to be also greater in the longitudinal than transverse direction, although an explicit evaluation of pesticide gradients in the transverse direction was not conducted in this study.

With the measured contaminant gradients in the vertical and longitudinal directions (Fig. 4) and assumption of uniform contaminant concentrations in the transverse direction, concentrations were interpolated across the 3-dimensional sediment volume. While we recognize that interpolation error can result from the assumptions in this analysis, we estimate that almost 30,000 m^3 of sediments in the uppermost 1.2 m possess concentrations of total DDT and total chlordane that lay above their ERL and ERM values (Fig. 5a,b). In contrast, no sediment volume exceeded the ERL for total PCBs, and about half of the sediment volume in the lake had total PCB levels below detection ($<1 \text{ ng g}^{-1}$) (Fig. 5c). These plots provide estimates of the volumes of sediment, e.g., that would need to be removed to remediate the largest concentrations of DDT or chlordane. For example, arbitrarily assuming a goal of removing all sediments that exceeded the ERM for total DDT by $10\times$, we see that one would need to remove about 20,000 m^3 of sediment (Fig. 5a). Removal of sediment with concentrations that exceeded the ERM for total chlordane by $10\times$ would require removal of a smaller volume (approximately 2500 m^3) from the basin (Fig. 5b). Since the average bulk density of the sediment in the upper 1.2 m of sediment is about 650 kg m^{-3} , one can also estimate the dry-weight mass of sediment (e.g., almost 19,000 metric tons if all sediments are $> \text{ERM}$ for total DDT or total chlordane was removed).

4. Discussion

Hydroacoustic measurements are widely used in bathymetric mapping of lakes as well as fishery assessments (Simmonds and MacLennan, 2006), and increasingly used to quantify sediment properties and distribution (Tegowski, 2005; Anderson and Pacheco, 2011). Information about the distribution and properties of sediments in a lake is important since sediment properties have a strong effect on water and habitat quality. Organic C content is often one of the most important properties, related to rates of internal nutrient recycling (Sondegaard et al., 2003) and sediment oxygen demand (Hatcher, 1986), and has also been shown to influence accumulation in benthos of PCBs, PBDE and other hydrophobic organic contaminants (e.g., Dinn et al., 2012). Early research found that the distribution, biological exposure and burial of particle-associated contaminants such as DDT, PCBs and many trace elements are intimately related to the distribution of organic C in lakes (Förstner and Wittmann, 1979; Karickhoff et al., 1979). The distribution of organic C within a lake is a complex function of water depth, basin slope, particle size, wind and wave action, and other factors (Blais and Kalf, 1995; Bloesch, 1995). Due to these factors, there is considerable spatial patchiness in lacustrine sedimentary environments (Downing and Rath, 1988), making it difficult to estimate the amount and extent of sediment organic carbon and potential contamination hotspots.

Anderson and Pacheco (2011) recently reported that the fractal dimension of the bottom echo was strongly correlated with the organic C content of bottom sediments in Lake Elsinore and San Dieguito Reservoir in southern California, with an r^2 value of 0.87, making hydroacoustic mapping a potentially valuable tool for developing sampling plans targeting hydrophobic organic contaminants associated with organic matter in sediments. The fractal dimension of the bottom echo was also strongly correlated with clay content and total N content of bottom sediment, as well as rates of phosphate and ammonium release and sediment oxygen demand of bottom sediments (Anderson and Pacheco, 2011). Other researchers have used E1' and E1 and related energy-based measures to distinguish sediments with differing hardness, roughness and grain size (e.g., Sternlicht and de Moustier, 2003). The hydroacoustic method thus holds promise for delineating different types of sediment based not only upon their physico-chemical characteristics, but also on related biogeochemical processes.

Table 4
Concentrations of organochlorine pesticides and PCBs in core samples.

Compound	Sediment concentration (ng g^{-1}) (dry-weight basis)				ERL ^a	ERL exceedance	ERM ^b	ERM exceedance
	Mean (n = 54)	Median	Range					
Total DDT	919.1	779.6	16.2–2914	1.58	54 (100%)	46.1	52 (96%)	
DDE	644.4	573.1	13.8–1637	2.2	54 (100%)	27.0	52 (96%)	
DDD	224.4	169.1	4.3–1212	2.0	54 (100%)	20.0	49 (91%)	
(pp) DDT	21.5	13.3	<0.1–77.2	1.0	46 (85%)	7.0	39 (72%)	
Total Chlordane	34.9	26.3	0.1–115.0	0.5	51 (94%)	6.0	26 (54%)	
Total PCB	4.5	3.1	<0.1–18.7	22.7	0 (0%)	180	0 (0%)	

^a ERL (effects range low).

^b ERM (effects range median) concentrations compiled by the NOAA (Buchman, 1999).

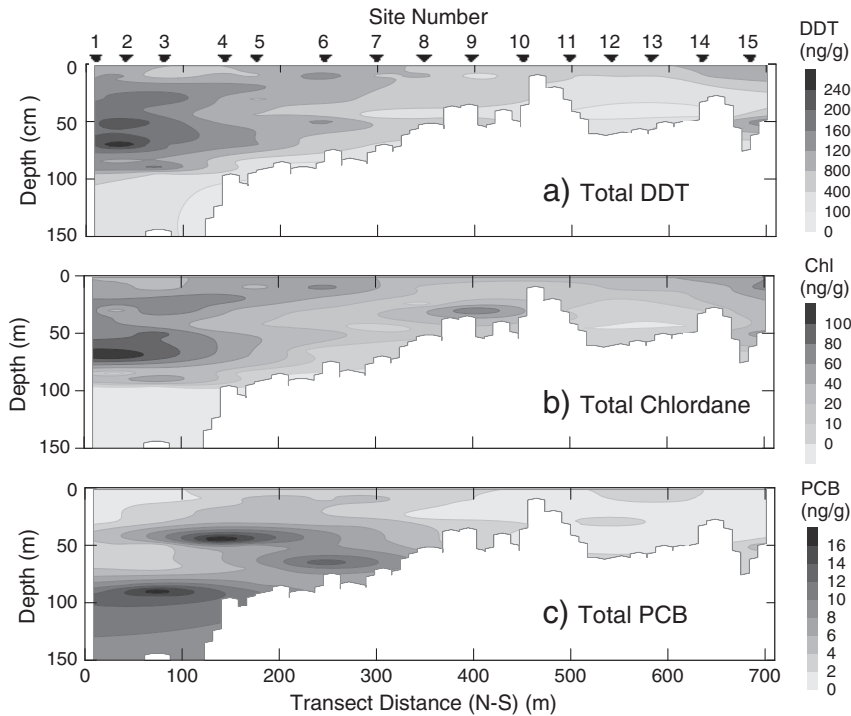


Fig. 4. Concentrations in sediments of McGrath Lake (dry-weight basis) of (a) total DDT, (b) total chlordane and (c) total PCB.

Hydroacoustic characterization of bottom sediments has previously been conducted as part of habitat assessments (e.g., Freitas et al., 2006), but has not generally been conducted as part of studies to examine the potential extent of sediment contamination. This study is thought to be among the first to incorporate hydroacoustic measurements to characterize sediment properties in the context of the investigation of OC pesticide contamination in a lake. The hydroacoustic measurements conducted in this study provided key information about McGrath Lake, including bathymetry, sediment thickness and sediment organic C. While these measurements cannot explicitly identify contamination nor account for variations in contamination inputs or emission sources, they can be used as a tool to help develop a sampling scheme, based upon the distribution of sediment organic C, to identify potential contamination hotspots. Such information

can also reduce the total number of samples collected, thereby reducing costs.

The 3-dimensional distribution of bottom sediments in the basin, coupled with OC pesticide and PCB measurements, also provided detailed insights into contaminant concentration–area–volume relationships that can be used to guide restoration efforts at McGrath Lake; this approach may also prove useful for other similarly contaminated water bodies.

McGrath Lake possesses very high concentrations of total DDT and total chlordane. Concentrations of these organochlorine pesticides were greatest at the north end of the lake and at 60–80 cm depth, with total DDT exceeding 2000 ng g^{-1} and total chlordane exceeding 100 ng g^{-1} (Figs. 3, 4). Generally much lower concentrations were found in the southern part of the lake, indicating greater deposition

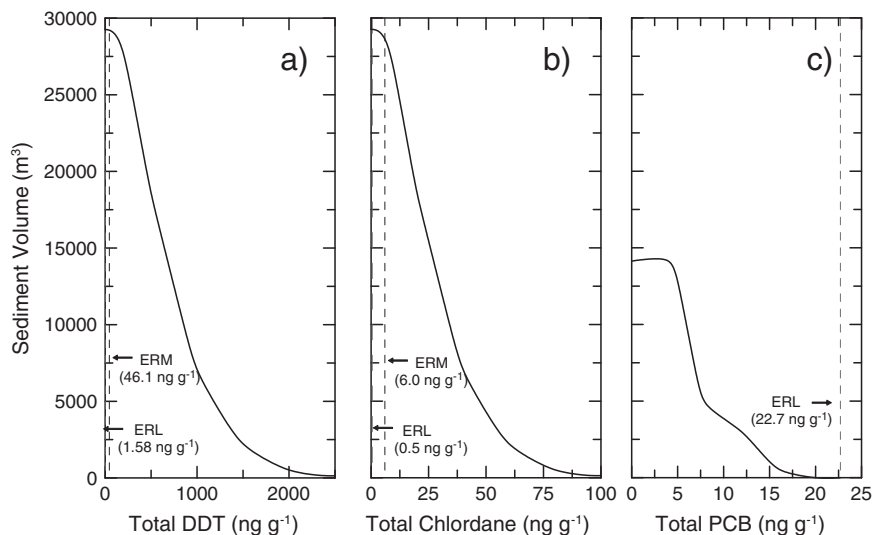


Fig. 5. Sediment volume vs. contaminant concentration: a) total DDT, b) total chlordane and c) total PCB.

of contaminants near the inflow at the north end, presumably associated with sedimentation of soil particles eroded from the watershed. Notwithstanding, total DDT and total chlordane concentrations were above their respective ERL values of 1.58 and 0.5 ng g⁻¹ for all or nearly all sites and depths. The reduction in total DDT and total chlordane levels near the surface presumably reflects the phasing out of their use in more recent times. Both pesticides were widely used beginning in the 1950s and banned in the 1970s. Their similar vertical (and horizontal) distribution in the lake is consistent with their use and their highly hydrophobic and recalcitrant chemical properties.

5. Conclusions

Hydroacoustic measurements of sediment thickness and organic C content can provide key insights to guide sampling and help assess the extent, distribution and volume of contaminated sediments in lakes and other aquatic systems that in the past have been cumbersome and costly to obtain through traditional sampling and analysis. The utility of this approach was assessed in a study of OC pesticide and PCB contamination at McGrath Lake, a shallow back-dune lake near Ventura, CA. Very high concentrations of DDT and chlordane were found in the sediment there (mean concentrations of 919.1 and 34.9 ng g⁻¹, respectively), as well as much lower total PCB concentrations (mean concentration of 4.5 ng g⁻¹). The hydroacoustic survey was utilized as a tool to create a sampling plan targeting potential hydrophobic contaminant hotspots in bed sediment, thereby reducing the number of samples required to fully assess the contamination extent. Using the knowledge of basin size and sediment properties obtained from the hydroacoustic survey and coupled with the measured contamination levels, it is estimated that ~30,000 m³ of sediment is present in the basin exceeding ERL and ERM values. While hydroacoustic measurements cannot explicitly quantify contaminant levels nor account for variations in past contaminant inputs or emission sources, the ability to estimate sediment properties such as organic carbon makes this a valuable tool in the planning and implementation of contaminated sediment sampling campaigns in lakes, reservoirs and estuaries. When combined with chemical contaminant measurements, the hydroacoustic data also provide information on the distributions and volumes of contaminated sediments vital to efficient and cost effective site remediation.

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