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DEVELOPMENT OF A PASSIVE, IN SITU, INTEGRATIVE SAMPLER FOR HYDROPHILIC ORGANIC CONTAMINANTS IN AQUATIC ENVIRONMENTS

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Abstract—Increasingly it is being realized that a holistic hazard assessment of complex environmental contaminant mixtures requires data on the concentrations of hydrophilic organic contaminants including new generation pesticides, pharmaceuticals, personal care products, and many chemicals associated with household, industrial, and agricultural wastes. To address this issue, we developed a passive in situ sampling device (the polar organic chemical integrative sampler [POCIS]) that integratively concentrates trace levels of complex mixtures of hydrophilic environmental contaminants, enables the determination of their time-weighted average water concentrations, and provides a method of estimating the potential exposure of aquatic organisms to the complex mixture of waterborne contaminants. Using a prototype sampler, linear uptake of selected herbicides and pharmaceuticals with log K_{ow}s < 4.0 was observed for up to 56 d. Estimation of the ambient water concentrations of chemicals of interest is achieved by using appropriate uptake models and determination of POCIS sampling rates for appropriate exposure conditions. Use of POCIS in field validation studies targeting the herbicide diuron in the United Kingdom resulted in the detection of the chemical at estimated concentrations of 190 to 600 ng/L. These values are in agreement with reported levels found in traditional grab samples taken concurrently.

Keywords—Polar organic chemical integrative sampler [POCIS] Integrative Pharmaceuticals Hydrophilic contaminants

INTRODUCTION

Current global population growth is creating an ever-increasing demand on potable water. To fulfill these requirements, water often is used, treated for release back into the environment, and reused by successive communities downstream. Restrictions on the concentrations of many pesticides, industrial chemicals, etcetera are in place to protect human health; however, such restrictions do not exist for many of the commonly used household chemicals, pharmaceuticals, and personal care products. Municipal wastewater treatment plants often do not remove these chemicals from the effluent and the treatment process can deconjugate metabolized forms of some pharmaceuticals to their biologically active form [1–2]. Research indicates that the large quantities of these polar organic chemicals (POCs), potentially associated with human, industrial, and agricultural usage enter aquatic systems on a global scale and may be responsible not only for acutely toxic effects, but also chronic abnormalities in aquatic organisms [1,3]. Until recently, there has been a lack of analytical methods with sufficient selectivity and sensitivity to identify accurately and quantitate these compounds in complex environmental matrices [4–6].

Many POCs may have adverse effects on aquatic organisms at low parts-per-trillion concentrations [7]. Due to the relatively high water solubility of POCs, modifications to many standard extraction and/or concentration methods are required. Use of techniques such as liquid–liquid extraction may result in unacceptable recoveries of POCs due to the low affinity of POCs for the organic solvent [8]. Solid phase extraction (SPE) sorbents, available as individual or mixtures of sorbents [8–10] and sorbents intertwined in a membrane disk [11–12; Jones-Lepp et al. (http://www.epa.gov/nerlesd1/chemistry/ppcp/trends.htm)] offer an attractive alternative for water sampling. Although these techniques often include the use of new specially modified resins for retention and recovery of polar organic compounds [9], sample collection represents only a few hours in time and does not mimic the continuous exposure of POCs to aquatic organisms. Extraction of several liters of water often is required to recover sufficient analyte mass for detection by most instrumental systems. If analyses are performed in the laboratory on a regular basis, the handling and transport of large volumes of water samples can be problematic, labor intensive, and may fail to detect episodic contaminant events. The determination of time-weighted average (TWA) concentrations, which is a fundamental part of an ecological risk assessment process for chemical stressors, may be impossible without extensive repetitive sampling. Sufficient repetitive sampling can be physically, logistically, and financially difficult, especially in remote areas. An in situ integrative sampling method is needed to enable estimates of TWA concentrations of POCs, sequester residues from episodic events commonly not detected with grab sampling, be used in situations of variable water conditions, and permit concentration of ultra-trace, yet toxicologically relevant contaminant mixtures over extended time periods.

Limited research involving the passive sampling of POCs has been performed. Kingston et al. used a C_{18} Empore disk

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covered with a polysulfone membrane encased in a polytetrafluoroethylene housing [13]. Müeller et al. are investigating the use of several types of Empore disks with and without a protective diffusive membrane (J. Müeller, National Research Centre For Environmental Toxicology, Coopers Plains, Australia, personal communication). Both of these samplers have advantages over traditional methods of sampling; however, they have limitations in their performance and range of chemicals sampled.

As an integral part of our ongoing environmental contaminants research [10,14–15; Jones-Lepp et al. (http://www.epa.gov/nerlesd1/chemistry/ppcp/trends.htm)], we developed the polar organic chemical integrative sampler (POCIS). This device consists of a solid sequestration medium enclosed within a microporous membrane for the integrative sampling of hydrophilic organic chemicals. The POCIS [16] was designed to mimic respiratory exposure of aquatic organisms to dissolved chemicals without the inherent problems of dietary assimilation of chemicals, metabolism, clearance of chemicals, avoidance of contaminated areas, and mortalities of test organisms. Thus, the POCIS is an abiotic device that enables estimation of the cumulative aqueous exposure to bioavailable hydrophilic organic chemicals and permits determination of the biologically relevant TWA concentrations in water.

Potential environmental contaminants chosen for this study were selected due to their abundant usage, range of polarities (log K_{ow}s < 4.0), and chemical and/or structural similarities to other compounds of interest. Diuron, isoproturon, atrazine, and diazinon are commonly used pesticides around the world. Diuron has been detected in surface and groundwater in the United States and is becoming a major issue of concern in both marine and freshwater resources of the United Kingdom, Europe, and Australia [17–19]. The chemicals levothyroxine, azithromycin, fluoxetine, and omeprazole were chosen as model pharmaceuticals due to their prolific use in the United States.

In this work, we evaluated various SPE sorbents and membrane materials to optimize the sampling and recovery of the model compounds. Laboratory-based calibration of the POCIS was performed for selected chemicals to generate sampling rate data. The combination of theoretical models and laboratory-derived sampling rate data allows for the estimation of ambient water concentrations from sequestered residues. Field-derived data demonstrate the applicability of the POCIS for environmental monitoring.

MATERIALS AND METHODS

Materials

Isolute ENV+ solid phase extraction resin was purchased from Jones Chromatography (Lakewood, CA, USA). Ambersorb 1500 was obtained from Rohm and Haas (Philadelphia, PA, USA). The S-X3 Bio-Beads (200–400 mesh) were purchased from Bio-Rad Laboratories (Hercules, CA, USA). Oasis HLB (poly[divinylbenzene]-co-*N*-vinylpyrrolidone) was supplied by Waters (Milford, MA, USA). Polyethersulfone (PES) membrane (0.1-μm pore size) was provided by Pall Gelman Sciences (Ann Arbor, MI, USA). All organic solvents were of Fisher Optima Grade or equivalent. Diuron and isoproturon were obtained from ChemService (West Chester, PA, USA). Azithromycin, fluoxetine, levothyroxine, and omeprazole were purchased from U.S. Pharmacopeia (Rockville, MD, USA). The ^{14}C atrazine (Pathfinder Laboratories, St. Louis, MO, USA; 0.0010 μCi/μl), ^{14}C diazinon (Novartis Crop Protection, Greensboro, NC, USA; 0.00111 μCi/μl), and ^{3}H ethynylestradiol (Life Science Products, Boston, MA, USA; 9.79×10^{-4} μCi/μl) also were used. Hereafter the use of atrazine, diazinon, and 17α-ethynylestradiol in the text refers to the radiolabeled analogs of these compounds.

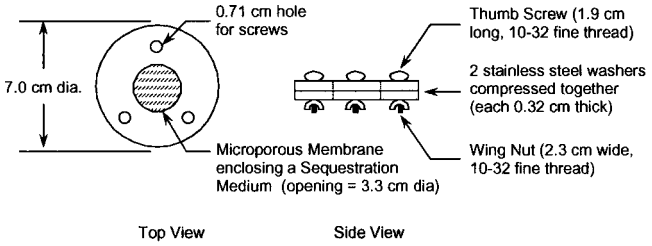

Fig. 1. Compression holder schematic. Standard configuration used in the laboratory calibration studies. Larger devices can be constructed to increase the sampling area by maintaining the membrane surface area–to–sorbent mass ratio.

Compression holder for membrane disk

The PES membrane used in the POCIS is not amenable to available sealing methods (i.e., heat, adhesives, etc.). Therefore devices were constructed of a suitable material (i.e., stainless steel or aluminum), that would physically compress the membrane layers together without competing for chemical uptake (Fig. 1). This compression seal is adequate, as none of the material held between the membrane layers was lost in any exposure and the surface area of perimeter diffusional pathway is minimal. In this study, the configuration of the device consisted of two rigid washers (3.3 cm i.d., 7.0 cm o.d., 0.3-cm thick) held together by three thumbscrews (10-32 size, 1.9-cm long) and wing nuts (10-32 size). The dimensions of the compression holder allow for the use of commercially available 47-mm membrane disks. The inner diameter of the washers provides maximum surface area exposure while still maintaining sufficient overlap to ensure a good seal. The total exchanging (chemical) surface area of the membrane (both sides) is ≅18 cm^2 per device. Thumbscrews and wing nuts were selected to allow construction and disassembly of the device by hand. Larger washers (5.1 cm i.d., 8.9 cm o.d.) also have been used in combination with larger membrane disks in order to increase the effective sampling surface area (≅41 cm^2) of the device. When using a larger surface area configuration, the mass of sorbent was increased proportionally to maintain a standard surface area–to–sorbent mass ratio, which is necessary for standardizing calibration/quantitation operations.

POCIS material preparation and construction

The PES membrane is cut from a roll into pieces slightly larger than the internal diameter of the compression holder. Up to 25 PES pieces are placed in a glass vessel to which solvent (40 ml per piece of membrane) is added. The PES is mixed by hand to disperse the pieces in the solvent and the vessel is stored at 40°C for 24 h. The process is repeated with fresh solvent two more times, after which the PES is placed on solvent-rinsed Al foil to dry. The solvent used is 20% methanol in water, followed by 100% methanol for the final two additions. The cleaned and dried PES is wrapped in a solvent-rinsed Al foil envelope, sealed in a solvent-rinsed metal can under argon and stored in a freezer at −20°C until needed.

The sorbents are cleaned in bulk by solvent washes in a gravity-flow glass chromatography column. Successive additions of 250 ml each of methanol, methyl-*tert*-butyl ether, dichloromethane, and methanol are added to the column. Once drained, the sorbent is transferred into an evaporating flask that is placed on a roto-evaporator at approximately 50°C under vacuum until all the solvent is removed and the dried sorbent is free flowing. The cleaned and dried sorbent is placed in a clean glass jar, covered with solvent-rinsed Al foil and a Teflon®-lined lid.

The individual POCIS units are constructed by forming a membrane–sorbent–membrane sandwich. A piece of PES is placed on the bottom compression holder washer. The known amount of the appropriate solid sorbent is placed on the center of the PES membrane. The second PES membrane is placed over the sorbent and the top compression holder washer is added. Thumbscrews and wing nuts are tightened to secure the holder and prevent loss of the solid sorbent. After construction, the POCIS are stored in solvent-rinsed metal cans under argon in a freezer at −20°C. Because the polymeric sorbents used in the POCIS are readily water wettable, they can be stored dry unlike silica-based sorbents (i.e., C_8 and C_{18}), which must first be conditioned to allow maximum interaction with water.

Standard POCIS configuration

The prototype design consisting of 18 cm^2–exposed membrane surface area and 100 mg of sequestration medium (i.e., sorbent) and a surface area per mass of sorbent ratio of ≅180 cm^2/g is designated as the standard configuration for all POCIS work. The device's sampling rates for individual chemicals are proportional to the effective membrane surface area exposed to the surrounding water. Laboratory-derived calibration data (i.e., sampling rate data) are only applicable to devices of common surface area-to-sorbent mass ratios resulting in the necessity of a standardized configuration. Selection of the membrane and/or sorbent material can vary dependent on the specific application; however, changing the type of membrane used likely will result in altered sampling rates. In cases where specialized sorbents with different specific gravities and/or sorbent capacities are used, a modification of the surface area–to–sorbent mass ratio may be necessary.

Analyte recovery optimization

The extraction and recovery of the test chemicals from the triphasic sorbent admixture (80:20 [weight:weight] Isolute ENV+:Ambersorb 1500 dispersed on S-X3 Bio Beads) and Oasis HLB sorbent were optimized. Pharmaceuticals and phenyl urea herbicides were tested as separate mixtures to simplify their analyses. Atrazine, diazinon, and 17α-ethynylestradiol were used individually. Samples of 20 to 50 ml of water were fortified with 1 to 5 μg of each chemical and passed through the sorbent beds prior to analyte elution with organic solvents. These concentrations were selected at levels above typical sequestered chemical residues from passive samplers to demonstrate that the sorbents had sufficient capacity. Analysis of the effluents from the columns generally resulted in concentrations of the chemicals below the detection limits of the corresponding instrumental techniques indicating the chemicals had been suitably retained by the sorbents. Recovery of the model compounds from the sorbent admixture was achieved by transferring the sorbents into glass gravity-flow chromatography columns (1 cm i.d.) fitted with glass wool plugs and stopcocks. Fifty ml of 1:1:8 methanol:toluene:dichloromethane were used to recover analytes from 200 mg of the sorbent admixture. Methanol was added in two successive 20 ml portions to 200 mg of the Oasis HLB sorbent for recovery of the pharmaceuticals. The collected eluates were reduced in volume by rotary evaporation with final volume adjustments and solvent exchanges made by evaporation under a gentle stream of high purity nitrogen. As these were laboratory-derived samples with minimal interferences, no sample cleanup procedures were necessary. A minimum of six replicates for each chemical were performed to provide a good statistical basis for review (Table 1).

Table 1. Recovery of selected analytes from the polar organic chemical integrative samplers (POCIS) sequestration medium. Values reported as percent recovery (standard deviation [SD])

Analyte	Sorbent composition	Procedural recovery percent (SD)
Atrazine	Triphasic admixture[a]	88 (1.0)[b]
Diazinon	Triphasic admixture[a]	98 (1.8)[b]
Diuron	Triphasic admixture[a]	92 (11)[c]
17α-Ethynylestradiol	Triphasic admixture[a]	97 (3.0)[b]
Isoproturon	Triphasic admixture[a]	99 (12)[c]
Azithromycin	Oasis HLB[d]	110 (28)[e]
Fluoxetine	Oasis HLB	95 (19)[b]
Levothyroxine	Oasis HLB	86 (26)[b]
Omeprazole	Oasis HLB	95 (16)[e]

[a] 80:20 (weight : weight) Isolute ENV + : Ambersorb 1500 dispersed on S-X3 Bio Beads (Bio-Rad, Hercules, CA, USA).
[b] $n = 12$.
[c] $n = 6$.
[d] Poly(divinylbenzene)-co-*N*-vinylpyrrolidone.
[e] $n = 8$.

Membrane evaluation

Separate devices constructed from low-density polyethylene, polyvinylidene fluoride, regenerated cellulose, an acrylic copolymer, nylon 66, hydrophilic polypropylene, and PES with the aforementioned sorbent admixture were tested as passive samplers. The samplers were placed in 1 L of water, magnetically stirred, and individually fortified with 17α-ethynylestradiol, atrazine, and diazinon. Exposure times ranged from 24 h to one week under stirred conditions. Analyte uptake was measured by monitoring water concentrations and analysis of the sampling devices following exposure by liquid scintillation counting (LSC). Visual inspection, sealing methods, and durability of the membranes also were considered during these evaluations.

POCIS calibration

Calibration studies to determine POCIS sampling rates for the test chemicals involved static renewal exposures of the samplers to each analyte in glass microcosms containing 1 L of water. A single prototype POCIS was placed in each microcosm. The water was fortified (5 μg of each test chemical) by adding the appropriate amount of chemical by syringe and thoroughly mixing prior to adding the POCIS. The water was replaced with freshly fortified water at regular intervals for the nonstirred and stirred exposures. The calibrations were performed in triplicate with a fourth microcosm containing nonfortified water serving as a background control blank. For the stirred exposures, the water was refreshed daily and for the nonstirred studies, every Monday and Friday. Average tem-

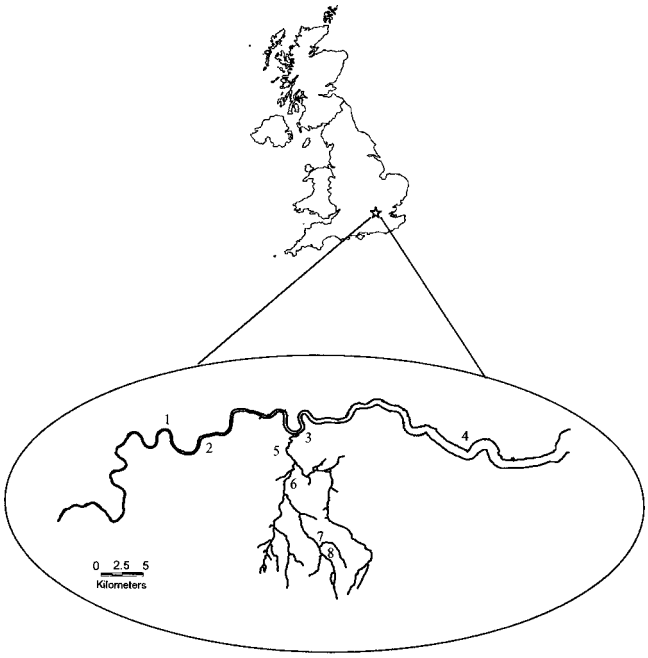

Fig. 2. Map of deployment sites along the River Ravensbourne and the Thames Tideway in the southern United Kingdom near London. Sites along the Thames include: the Polo (1), Cadogan (2), Greenwich (3), and Purfleet (4). River Ravensbourne sites are Deptford Bridge (5), Ladywell Park (6), Glassmill Lane (7), and Hayes Lane (8). Polar organic chemical integrative samplers (POCIS) were deployed at each site for 30 d during May of 2001.

peratures of the test systems were 27 and 23°C for the stirred and nonstirred exposures, respectively. Diuron and isoproturon were calibrated as a mixture and the pharmaceutical tests were performed with a separate chemical mixture. Renewals were continued for up to 56 d to demonstrate continuous uptake over prolonged periods by determining the analyte sampling rates at 7, 14, 28, and 56 d.

Proof-of-concept field deployment

The POCIS were deployed at eight sites throughout the Thames Tideway and River Ravensbourne catchment basin in southern England for a period of 30 d (Fig. 2). The POCIS, mounted in protective deployment canisters constructed from perforated PVC pipe, were suspended in the water column by cabling to nearby structures. The samplers from one site (Greenwich) were lost prior to retrieval. The samplers, in air-tight metal cans, were stored frozen and transported on blue ice to and from the field. Quality control measures including fabrication blanks, field blanks, and laboratory positive control samples were used to ensure the reliability of the data. Extraction of the deployed POCIS in the laboratory was performed as described for the recovery of the model compounds from the sorbent admixture. Analysis of the hormones and hormone metabolites was achieved using the high-performance liquid chromatography (HPLC) system subsequently described for the herbicides monitoring a wavelength of 281 nm.

Herbicide analysis

Diuron and isoproturon analyses were performed on a HPLC system consisting of a Hewlett-Packard Series II 1090 Liquid Chromatograph with a diode array detector (Hewlett-Packard, Palo Alto, CA, USA) with the ChemStation for LC (Agilent Technologies, Palo Alto, CA, USA). A Phenomenex Luna C_{18} analytical column (150 × 4.6 mm, 5-μm diameter particle) and a Phenomenex Security Guard C_{18} cartridge (Phenomenex, Torrance, CA, USA) with a 55:45 water:acetonitrile mobile phase at flow of 1 ml/min was maintained at 30°C. Detection occurred at 254 nm for diuron and 242 nm for isoproturon. Limits of detection for diuron and isoproturon are 2.0 and 1.3 ng on column, respectively, as described by Keith [20].

Pharmaceutical analysis

The POCIS extracts were analyzed for the pharmaceuticals (fluoxetine, levothyroxine, azithromycin, and omeprazole) by μ-liquid chromatography–electrospray/ion trap mass spectrometry. The microcapillary columns were prepared in-house (U.S. Environmental Protection Agency, Las Vegas, NV, USA). The 160-μm i.d. (360-μm o.d.) fused silica columns (Polymicro Technologies, Phoenix, AZ, USA) were packed with approximately 10 to 12 cm of 5-μm ODS-Hypersil (Shandon, Astmoor, UK), as described by Moseley et al. [21]. An isocratic mobile phase of 80% methanol, 19% water, and 1% acetic acid was used. A ThermoQuest Finnigan LCQ (Thermo Electron, San Jose, CA, USA), configured with an electrospray ion source and an ion trap analyzer, was operated in the positive ion mode for the detection of the pharmaceuticals. The electrospray needle was run at approximately 4.5 to 5.2 kV, and the ion trap mass spectrometry scanned from 130 to 830 amu (full-scan mode) in 3-μ scans with an ion injection of 200 ms. On-column detection limits for azithromycin, fluoxetine, levothyroxine, and omeprazole were 4.0, 20, 0.72, and 1 ng, respectively, as described by MacDougall and Crummett [22].

Radiometric analysis

Determinations of atrazine, diazinon, and 17α-ethynylestradiol were performed using a Beckman LS 6500 liquid scintillation counter (Beckman Instruments, Irvine, CA, USA).

THEORY AND MODELING

Using passive sampling devices and assuming calibration data are available for the appropriate exposure conditions, ambient water concentrations of analytes can be estimated from their integrative (linear uptake) sampling rates (i.e., no significant loss of accumulated residues), equilibrium steady state partition coefficients, and the rates of residue clearance or elimination. Accumulation of chemicals by passive samplers typically follows first-order kinetics, which is characterized by an initial integrative phase, followed by curvilinear and equilibrium partitioning phases [14]. Selection of the appropriate method to use is dependent on exposure duration and performance of the sampling device.

In the integrative sampling phase, the sampling device acts as an infinite sink for contaminants of interest and analyte uptake is linear. This approach provides an estimate of the TWA concentration of contaminants during a specified exposure period. Unlike samplers that rapidly achieve equilibrium (characterized by high loss rates and low capacity), chemical residues from episodic events during the integrative part of an exposure are retained in the POCIS. Thus the rate of analyte loss is very small and the times to reach equilibrium are very large. The uptake rate constant (k_u, L, or ml/d · g) and sampling rate (R_S, L, or ml/d) are independent of environmental concentration [14].

Preliminary tests [23] indicated that analyte uptake is under aqueous boundary layer control. Using experimental condi-

tions to enhance uptake rates or lower resistance to solute mass transfer (i.e., stirring to thin the aqueous boundary layer), the results of the exposure studies indicated that for all of the test chemicals used, the POCIS remained in the linear uptake phase at 28 d, with no indication of when sampling becomes curvilinear. Therefore, the POCIS sorbent acted as an infinite sink for these contaminants and a linear uptake model was used for derivation of sampling rates (water concentrations were determined by an independent method) and calculation of ambient water concentrations.

Huckins et al. [14] formulated the following equation for integrative (i.e., linear) sampling by a passive sampling device:

$$C_W = C_S M_S / R_S t \quad (1)$$

where C_W and C_S are the analyte concentration in the water and sorbent, respectively, M_S is the mass of the sorbent, and t is time in days. The formulation of the sampling rate term (R_S) in Equation 1 changes depending on whether uptake is under boundary layer control or membrane control. Under boundary layer control,

$$R_S = (D_W/\ell_W)A \quad (2)$$

where D_W is the diffusion coefficient in water, ℓ_W is the effective thickness of the aqueous boundary layer, and A is the surface area of the sampling device. Under membrane control,

$$R_S = (D_M/\ell_M)\, K_{MW} A \quad (3)$$

where D_M is the diffusion coefficient in the membrane, K_{MW} is the equilibrium membrane–water partition coefficient, and ℓ_M is the thickness of the membrane. Use of Equation 1 is valid during exposure periods of $\leq$1 half-time (time to reach one-half of the equilibrium concentration) and after steady state flux of chemicals into the sampler has been achieved.

Mass transfer through a microporous membrane, such as the PES used in the POCIS, can follow a biphasic pathway with analyte transport through both water-filled pores and the polymer matrix. Assuming steady state and no biofouling, the flux (mass per unit time) of solutes through the membrane can be described as a weighted average of both water-filled pores and the polymer matrix pathways.

$$Q_o/t = C_W(D_{IS}A/\phi_{IS}) = C_W(D_M K_{MW} A[1-\theta]/\phi_M + D_{IM}A\theta/\phi_{IM})$$
$$= C_W(D_W A/\ell_w) \quad (4)$$

where Q_o is the total mass of chemical sampled by the POCIS sorbent; θ is the porosity factor, which we assume is 0.7 for PES membranes, based on free volume estimates; ϕ_M and ϕ_{IM} are the length of the diffusional pathways through the membrane matrix and the water-filled interstitial spaces in the membrane, respectively; D_{IM} is the diffusion coefficient in the membrane interstitial water, for which we assume $D_{IM} \cong D_W$; and D_{IS} and ϕ_{IS} are the diffusion coefficient and length of the diffusional pathway, respectively, for the boundary layer associated with the sorbent. This relationship assumes the sorbent acts as an infinite sink for sequestered chemicals. For compounds that are less than 400 Daltons, the main determinant in which pathway (i.e., interstitial water or membrane) is dominant is the magnitude of the K_{MW}. Unlike ℓ_W, the terms ϕ_M, ϕ_{IM}, and ϕ_{IS} include a tortuosity factor. For example,

$$\phi_{IM} = m_t \tau \quad (5)$$

where m_t is the hydrated membrane thickness and τ is the tortuosity factor.

The mass transfer steps for analyte uptake by POCIS include movement through the aqueous boundary layer, the biofilm (if present), diffusion through the water-filled membrane pores and through the membrane matrix, and movement through the boundary layer associated with the sequestration phase (sorbent). The resistance to mass transfer for each step is additive [14]. We assume that the water in the membrane pores remains essentially stagnant, regardless of the flow conditions of the surrounding bulk water. As the flow/turbulence increases at the membrane surface, the effective thickness of the external (membrane) boundary layer and sorbent-associated boundary layer decreases, which reduces impedance to mass transfer and thereby increases the sampling rate. Note that the effect of flow/turbulence may differ between the external (membrane) and internal (sorbent) aqueous boundary layers because of the buffering effect of the membrane and housing. Concurrently, flow/turbulence can thin the effective thickness of these boundary layers enough to switch rate control to the water-filled membrane pores or to the membrane matrix. At this point, the chemical sampling rates will become constant regardless of increases of the flow/turbulence conditions at the membrane surface (assumes constant temperature and biofouling levels).

Based on relationships such as the Hayduk and Laude Equation [24], analyte diffusion coefficients across the aqueous boundary layer are expected to be directly proportional to temperature. Although mass transfer through the aqueous boundary layer is much more complex than simple molecular diffusion, this modeling approach is reasonable for a first approximation. The Hayduk and Laude Model provides estimates of temperature-mediated changes in aqueous diffusivity with an absolute error of $<$6% and is given by

$$D_W = 1.326 \times 10^{-4}/(\eta_W^{1.14}\, V_B'^{0.589}) \quad (6)$$

where η_W is the viscosity (inversely related to temperature) of water for a specific temperature and V_B' is the molal volume of the analyte. The molal volumes for each analyte were calculated using the LeBas method of summing volume incremental values for the individual components of the molecule. The D_W values were calculated for each test chemical using η_W values for 10, 20, and 30°C. Increases in the D_W of 1.30 to 1.35-fold were calculated for 10 to 20°C and 20 to 30°C, respectively. Over the 10 to 30°C range, D_W increased by 1.75-fold. Using these values and the relationship between D_W and R_S as shown in Equation 2, a theoretical maximum twofold increase in the D_W that correlates to a 50% change in the R_S over a 20° temperature range would be expected.

The buildup of a biofilm on a membrane surface is another potential barrier to analyte mass transfer. The thickness of a biofilm will vary from exposure to exposure depending on the environmental conditions and membrane properties. The presence of a thick biofilm can cause significant decreases in the sampling rate of hydrophobic compounds [14]. However, PES membranes exhibited an apparent resistance to biofilm development and any particulate or biofilm layer present did not significantly impede the uptake of 17α-ethynylestradiol [23]. This is partly because resistance to mass transfer in any biofilm is greatest for very hydrophobic compounds, whereas hydrophilic compounds encounter little impedance [14].

The membrane itself can contribute a significant resistance to mass transfer. As previously discussed, the analyte flux through the membrane occurs via a biphasic mechanism of transport in water-filled pores and diffusion in the polymeric

matrix (Eqn. 4). The average thickness of the PES membrane is approximately 130 μm, however, the membrane pore length follows a torturous path through the thickness of the membrane. Based on mass/volume measurements and density information [25], the estimated open pore volume of the PES membrane used in POCIS construction is 76.5%. Dissolution of the chemical species into and migration through the polymer matrix occurs for chemicals in which the sampling rate is under membrane control. For chemicals under membrane control, the sampling rate remains nearly constant regardless of the surrounding flow/turbulence conditions; however, this appears to be of minimal importance in the uptake of waterborne chemicals by the POCIS.

RESULTS AND DISCUSSION

Analyte recovery optimization

Polymeric and carbonaceous sorbents traditionally used for SPE potentially are useful as a sequestration medium in integrative sampling devices. Various sorbents and combinations of solvents of different elutropic strengths were evaluated to determine their applicability for use with the POCIS [23]. The sequestration medium selected for most of the work presented hereinafter consists of a triphasic admixture of a hydroxylated polystyrene–divinylbenzene resin (Isolute ENV+) and a carbonaceous adsorbent (Ambersorb 1500) dispersed on a styrene divinylbenzene copolymer (S-X3 Bio-Beads) commonly used for size exclusion chromatography. The dispersion of finely ground Ambersorb 1500 on S-X3 (S-X3/A-1500) was used to overcome the lower recoveries of the model chemicals by reducing the total mass of the carbonaceous sorbent present. The S-X3/A-1500 was prepared by an adaptation of the procedure described by Huckins et al. [26]. Using this procedure, the average surficial loading of A-1500 on the S-X3 gel is 5% by weight. Overall, the sorbent admixture is comprised of a 20:80 ratio by weight of the S-X3/A-1500 and Isolute ENV+, respectively. The admixture of S-X3/A-1500 and Isolute ENV+ proved to be superior to the individual sorbents for the uptake and recovery of the selected classes of polar organic compounds (i.e., pesticides, hormones, etc.) by reducing the analyte loss while maintaining adequate analyte recoverability. The retention and recovery of various chemical classes from the sorbent admixture demonstrated the reproducibility of the method (Table 1).

Sampling for highly polar organic molecules (i.e., pharmaceuticals with multiple chemical functional groups, pK_as, etc.) requires the use of alternative sorbents. The recovery of these pharmaceuticals from the carbonaceous component of the triphasic admixture is problematic and precludes its use in such situations. The Oasis HLB SPE sorbent, consisting of a hydrophilic–lipophilic balanced copolymer of [poly(divinylbenzene)-co-*N*-vinylpyrrolidone], is well-suited for such applications. Laboratory investigations confirmed the ability of Oasis HLB to effectively retain and recover pharmaceuticals in water ranging from antidepressants to macrolide antibiotics. Recoveries from the Oasis HLB sorbent are listed in Table 1.

Membrane evaluation

The microporous POCIS membrane acts as a semipermeable barrier between the sorbent and the surrounding environment. The membrane allows polar organic solutes to pass through to the sorbent, while particulate matter, colloids, and biota (including microorganisms) with cross-sectional diameters greater than the membrane pore diameter will be excluded selectively. Direct contact of these excluded materials with the sorbent may result in a site-specific bias of apparent contaminant concentrations in the sorbent, reduces uptake due to greater biofouling of the sorbent than the PES membrane, and potential interferences during sample processing and analysis. Several commercially available polymeric membranes (i.e., low-density polyethylene, polyvinylidene fluoride (PVDF), regenerated cellulose, an acrylic copolymer, nylon 66, hydrophilic polypropylene, and PES) were evaluated for use in a hydrophilic integrative sampler (Table 2). Low-density polyethylene and polyvinylidene fluoride, two hydrophobic polymers, were attractive for their availability as layflat tubing and amenability to heat sealing; however, neither demonstrated a sufficient affinity for sampling the model compounds. Regenerated cellulose is a hydrophilic membrane commonly used in dialysis applications. Although uptake of the test compounds was noted, cellulose is known to readily biodegrade in some environments and therefore was eliminated from consideration. Kingston et al. [13] observed similar resistance to the uptake of atrazine and diuron using low-density polyethylene, polyvinylidene fluoride, and cellulose. Uptake of the polar analytes was observed using an acrylic copolymer. Similar to PES, the acrylic copolymer membrane is available as a microporous membrane filtration disk and the material is not amenable to heat sealing. Although its sampling ability was attractive, the acrylic copolymer's minimum pore diameter of 0.2 μm is twofold larger than PES and, therefore, would exclude less unwanted macromolecules, biogenic materials, etc., from reaching the sorbent. The hydrophilic nylon 66 membrane also demonstrated an excellent uptake of the polar compounds. However, this membrane lacked the strength and durability of other membranes studied and was removed from consideration. Both hydrophilic polypropylene and PES are microporous hydrophilic membranes. Initial exposures demonstrated the ability of these membranes to sample polar organic contaminants. The hydrophilic polypropylene lacked the durability necessary for long-term integrative sampling. After 24 h in the stirred exposures (simulating a moderately turbulent environment), the membrane became very weak and tore with the slightest touch. Of the membranes studied, PES exhibited the best combination of high analyte uptake rates, minimal surficial bio-

Table 2. Comparison of analyte uptake into sampling devices constructed with various membrane compositions following a 24-h period

Membrane composition	Diazinon % uptake (SD[a])	Ethynylestradiol % uptake (SD)	Atrazine % uptake (SD)
Polyethersulfone	36 (2.7)	41 (6.87)	27 (6.9)
Acrylic copolymer	19 (5.3)	20 (3.8)	ND[b]
Cellulose	20 (3.8)	27 (9.1)	ND
PVDF[c]	24 (7.8)	7.5 (1.2)	ND
Hydrophilic polypropylene	31 (3.7)	40 (4.2)	16 (16)
Nylon 66[d]	48 (4.3)	28 (6.3)	19 (1.9)
Polyethylene[d]	ND	26 (9.3)	ND

[a] SD = standard deviation of triplicate trials.
[b] ND = not determined, experiments were not performed for this analyte.
[c] PVDF = polyvinylidene fluoride.
[d] Nylon 66 and polyethylene exposures were conducted for a one-week period.

Table 3. Experimentally determined sampling rates (R_S) for a single polar organic chemical integrative sampler (POCIS) of 18 cm^2 exposed surface area, expressed as liters of water cleared of analyte per day, under quiescent (nonstirred) and turbulent (stirred) conditions. Values reported are the average sampling rate in liters per day (standard deviation, $n = 3$)

Analyte	R_S from quiescent renewals (L/d)	R_S from turbulent renewals (L/d)
Diuron	0.005 (0.002)	0.045 (0.016)
Isoproturon	0.015 (0.003)	0.086 (0.008)
Azithromycin	0.021 (0.006)	0.120 (0.075)
Fluoxetine	0.012 (0.007)	0.086 (0.023)
Levothyroxine	0.009 (0.008)	0.053 (0.028)
Omeprazole	0.007 (0.004)	0.030 (0.008)

fouling, and membrane durability necessary for long-term integrative sampling of polar organic chemicals.

POCIS calibration

To determine sampling rates of the selected chemicals, studies were performed by placing the POCIS in water fortified with the test compounds under nonstirred (stagnant or quiescent) and stirred (turbulent) conditions. The chemical sampling rates (R_S) were determined by measuring the analyte mass sequestered per POCIS after 7, 14, 28, and 56-d sampling intervals (Table 3). Potential routes for removal of analyte from the water (i.e., sorption to the walls of the glass container, metal components of the sampler, etc.) other than sequestration by the POCIS were examined by solvent-rinsing the surfaces and analyzing the rinsates for the test chemicals. In all cases, traces of the test chemicals detected were negligible. The renewal intervals were selected to maintain a water concentration greater than half the equilibrium concentration for the selected chemical(s), thereby sustaining integrative sampling. Exploratory tests measuring the chemical uptake over a few days provided a rough estimate of the sampling rate. These data were used to set up a renewal schedule that allowed the nominal chemical concentration to decrease by no more than one-eighth of the original value. For example, azithromycin has a sampling rate of 0.120 L/d (stirred), therefore in one day, 120 of the 1,000 ml of water is cleared of chemical. Daily renewals of this water ensured that the time-weighted mean water concentration is maintained at levels close to the nominal concentration. Analyte R_S values were calculated for each sampling interval and an average sampling rate was determined for each compound for the nonstirred and stirred exposures (Table 3).

Exposures under quiescent (nonstirred) conditions exhibited a linear uptake of the targeted analytes by the POCIS at 56 d. Under turbulent (stirred) conditions diuron and isoproturon continued to exhibit linear uptake ($r^2 = 0.993$ and 0.994, respectively) at 56 d. The pharmaceuticals all were within the linear phase at 28 d and at 56 d azithromycin and levothryoxine ($r^2 = 0.988$ and 0.944, respectively) appeared to be linear. Fluoxetine and omeprazole may continue to be in the linear phase at 56 d ($r^2 = 0.827$ and 0.798, respectively); however, additional data points would be required to make a definite conclusion. Typically, sampling periods do not exceed 28 d; therefore, that data indicates that for the targeted compounds, the POCIS remains in the linear (integrative) phase of sampling.

The performance of the exposure vessel for generating relevant POCIS calibration data was compared to other test systems and the data generated were validated by comparison of the estimated water concentrations to data from accepted methods. The use of a stirred vessel, such as used for the POCIS, to generate calibration data for passive samplers has been well-documented in the peer-reviewed literature. Booij et al. [27] and Rantalainen et al. [28] both designed test systems that were stirred to provide flow/turbulence during the calibration of semipermeable membrane devices for hydrophobic organic chemicals such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, dioxins, and furans. Brumbaugh et al. [29] used a similar static renewal approach for the calibration of two passive samplers for metals. The stabilized liquid membrane device was calibrated for the metals Cd, Co, Cu, Ni, Pb, and Zn under both stirred and nonstirred conditions. The passive integrative mercury sampler was calibrated for neutral mercury in water using a nonstirred vessel [30]. The group of Davison and Zhang also used stirred vessels to calibrate the diffusive gradients in thin film passive samplers for labile metals [31,32].

The POCIS calibration data generated by the stirred renewal system were validated by comparing estimated water concentrations of select chemicals to data obtained by independent laboratories using accepted, standardized sampling protocols. Petty et al. [15] reported atrazine concentrations estimated from POCIS residues to be 0.93 ppb compared to a reported value of 1.16 ppb at a nearby site from the U.S. Geological Survey's NASQAN database (http://water.usgs.gov/nasqan/). Data presented describing the proof-of-concept field deployment (Table 4) showed that the estimated water concentrations for diuron and isoproturon were in general agreement with results from grab samples taken at identical sampling same

Table 4. Concentrations of selected contaminants isolated from polar organic chemical integrative sampler (POCIS) extracts deployed in the River Ravensbourne and the Thames Tideway in southern England

Deployment site	Diuron ng/L[a]	Isoproturon ng/L[a]	17β-Estradiol ng/POCIS	17α-Ethynylestradiol ng/POCIS	Estriol ng/POCIS	Estrone ng/POCIS
Deptford Bridge	960 [580][b]	<MDL [<40][b]	150	<MQL[c]	<MDL[c]	<MQL[c]
Glassmill Lane	110	<MDL[d]	210	<MDL[c]	<MDL[c]	<MDL[c]
Hayes Lane	<MQL[d]	<MDL[d]	170	<MDL[c]	<MDL[c]	<MDL[c]
Ladywell Park	740	<MDL[d]	590	<MQL[c]	<MDL[c]	<MQL[c]
Cadogan	350	81	420	<MDL[c]	<MDL[c]	<MQL[c]
The Polo	190 [170][b]	23 [110][b]	<MQL	<MDL[c]	<MDL[c]	<MQL[c]
Purfleet	600 [470][b]	50 [74][b]	190	<MDL[c]	<MDL[c]	<MDL[c]

[a] Laboratory-derived calibration data were used to estimate the ambient water concentrations (ng/L) of diuron and isoproturon.
[b] Values in brackets are average water concentrations from 1 L grab samples taken during the POCIS deployment period.
[c] For the hormones and metabolites, the method detection limit (MDL) is 5.0 ng on-column and MQL is 25 ng on-column.
[d] The MDL and method quantitation limit (MQL) for diuron and isoproturon are 2.0 and 1.3 (MDL) and 10 (MQL) ng injected on-column.

sites during the POCIS deployment period by scientists at the Environment Agency of England and Wales. A 5-d POCIS calibration for a suite of polar herbicides was performed using a stirred vessel containing 8 L of water (F. Stuer-Lauridsen, COWI A/S, Denmark, personal communication). The COWI A/S sampling rate data for atrazine, simazine, and terbuthylazine were within 13% of preliminary data generated using the test system described in the manuscript (D.A. Alvarez, unpublished data). The similarity of the data between water concentrations estimated from POCIS calibration data and that from traditional sampling protocols along with the agreement of preliminary calibration data generated by two independent laboratories indicate the exposure system described in this manuscript was suitable for the measurement of POCIS sampling rates.

Analyte uptake for the test chemicals largely was under aqueous boundary layer control as indicated by the four- to ninefold increase in sampling rates with stirring (i.e., increased turbulence, see Table 3). If the uptake was controlled by analyte diffusion through the membrane, the R_S essentially should be constant regardless of the water turbulence. Having a sampler under aqueous boundary layer control requires calibration data at various flow/turbulence conditions or the use of a permeability-performance reference compound(s) [33]. Attempts to incorporate a permeability-performance reference compound into the current POCIS configuration has been unsuccessful (D.A. Alvarez, unpublished data) due to the strong analyte retention of the sorbents. Stephens et al. have had some success with the permeability-performance reference compound approach for polar compounds by using the less retentive C_{18} Empore disk as the sequestration medium and deuterated atrazine as the reference compound (B.S. Stephens, National Research Centre For Environmental Toxicology, Coopers Plains, Australia, personal communication). Because the boundary layer appears to control uptake rates, composition of the POCIS sorbent does not effect sampling rates, provided the sorbent has sufficient capacity to act as an infinite sink for a particular chemical. Assuming the same membrane material is used and exposure conditions are similar, various sorbents can be used in POCIS without generating new calibration data. The use of several devices and/or devices with increased surface area for analyte sampling would increase proportionately the total volume of water cleared of chemical. This approach provides a greater cumulative analyte mass available for analysis. Implicit in this approach is the assumption that the analytical interferences do not increase to a level that precludes analysis.

Proof-of-concept field deployment

As part of an ongoing monitoring project for phenyl urea herbicides (i.e., diuron and isoproturon) in the Thames Tideway and the River Ravensbourne in the United Kingdom by the Environment Agency of England and Wales, POCIS were deployed for a period of 30 d at selected sites (Fig. 2). Diuron was detected in all POCIS samples with estimated water concentrations of up to 960 ng/L (Deptford Bridge, UK). Isoproturon was measured at the three sites in the Thames Tideway ranging from 23 to 81 ng/L. Scientists at the Environment Agency collected 1-L grab samples of the river water at Deptford Bridge, The Polo, and Purfleet (UK) concurrently with the POCIS deployment (Table 4). Quality control procedures indicated that no measurable bias was introduced into the analysis of the targeted analytes. The sampling sites all were flowing systems with significant turbulence; therefore, the laboratory-derived sampling rates for turbulent systems were used in the calculation of ambient water concentrations. Comparison of the results from the two sampling methods shows an agreement in the magnitude of the analyte water concentrations with less than a 1.7-fold difference between the techniques in all but one case. Differences in these values are the result of comparing a single point-in-time sample to a TWA concentration over an extended period. In all cases, the estimated analyte concentrations determined from residues sequestered in POCIS were below the European Union's prescribed Environmental Quality Standards of 2.0 μg/L for both diuron and isoproturon. The POCIS samples also were analyzed for selected estrogenic hormones. In all samples, the naturally occurring hormone 17β-estradiol was detected at levels up to 590 ng/POCIS. The metabolite estrone and the synthetic hormone 17α-ethynylestradiol both were detected at several sites but at levels below the method quantitation limits.

Petty et al. [15] describes a separate deployment in which POCIS were placed in a constructed wetland system used for the final polishing of treated wastewater. Chemical residues of atrazine, hydroxyatrazine, 17α-ethynylestradiol, ibuprofen, and caffeine were identified from the POCIS extracts. The extracts were tested for their estrogenic potential by use of the yeast estrogen screen. In all cases, the extracts from deployed POCIS exhibited a significant estrogenic response.

CONCLUSION

The development and subsequent field evaluation of the POCIS suggests that this passive in situ device is a viable option for the integrative sampling of hydrophilic organic contaminants. This prototype sampler may be preferable to standard sampling regimes as it provides TWA concentrations for analytes of interest, samples the bioavailable fraction of chemicals from the water column, and requires no power, maintenance, or supervision during deployment. Generating a sufficient number of samples to estimate TWA concentrations by traditional methods is imprudent logistically and financially as part of a regular monitoring program. Calibration data generated at various flow conditions and/or the use of permeability/performance reference compounds will allow for accurate estimation of ambient water concentrations. Extracts from the POCIS can be analyzed by common instrumental techniques with minimal sample manipulation and can be employed in bioindicator tests to screen the toxicological significance of complex chemical mixtures. Proof-of-concept deployments of the POCIS in various aquatic systems have been successful for the integrative sampling of hydrophilic contaminants such as atrazine, diuron, and 17β-estradiol. Comparison of POCIS data for diuron and isoproturon to data generated from an independent grab-sampling program demonstrate that the POCIS can provide accurate data on the concentrations of targeted analytes. Due to the quality of the data obtained and ease of use, the POCIS technique has the potential to become the standard for global water quality monitoring.

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