

An inexpensive, automatic, submersible water sampler

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Abstract

Currently available water samplers are manually actuated, can only be deployed onshore, limiting their use to small or developed water bodies, or are designed for deployment in the deep sea, making them large and expensive. The automatic submersible water sampler described here is small, lightweight, actuated by a micro-processor, and inexpensively and easily constructed. The sampler consists of a pressure case, sample containers constructed of 10 spring-loaded 60 mL syringes connected to solenoid valves, and electronics to control opening and closing of the solenoid valves. Vacuum in the syringes keeps the springs compressed while the solenoid valves are closed. When a valve opens, the spring expands and draws water past a screen and/or filter into the syringe. Once the syringe is filled, the solenoid valve closes, storing the sample. More than one syringe can be opened simultaneously if more than 60 mL are required. Preservatives can be added to the syringe prior to deployment. Some environments where it could be used include karst aquifers, lakes, large rivers, and estuaries.

In many hydrologic systems, natural and induced changes in the chemical composition of water can provide information on flow paths and water-rock interactions. Observations of these chemical changes require samples of water, but sampling can be complicated by a variety of logistical problems related to access to the water body or limitations in time. For example, sampling at high frequency in systems with rapidly changing conditions or across widely spaced regions may be impossible with limited personnel. Long-term studies may require numerous samples, which could be prohibitively costly and difficult to collect by hand in remote areas. Sampling is commonly restricted by access in certain water bodies such as large lakes, rivers, estuaries, and water-filled caves and conduits. These complications can be alleviated in certain environments through automatic sampling of the water with use of a variety of commercially available or homemade samplers. Samplers that are currently available, however, are designed primarily for use on land, in the deep sea (e.g., Sholkovitz 1970; Friederich et al. 1986; McKinney et al. 1997; Bell et al. 2002), or are manually activated (e.g., Broenkow 1969; Heaney 1974; Blakar 1979; Cline et al. 1982). Samplers designed for use on land typically are deployed in developed water systems, such as storm sewers and wastewater treatment plants, where access and placement of the instruments is simplified. Samplers that are used in the deep sea must be suffi-

ciently robust to withstand high pressures and corrosion of seawater, which increases their size, weight, and cost. These designs can limit wide applications within natural water systems, particularly in remote areas, large water bodies, or in locations where access is difficult or restricted.

We describe here a new type of automatic water sampler designed primarily for collection of water in shallow systems (lakes, rivers, caves, estuaries). It has several benefits over previous designs including small size, robustness, and ease of deployment and operation. Its small size makes it lightweight, easily transported and deployed, and simple to construct. Because the sampler is inexpensive, numerous samplers could be deployed for a single project. The sampler is deployed directly in the water to be sampled, opening sampling capabilities blocked to shore-based samplers.

Materials and procedures

Several types of earlier sampler designs and their uses and limitations are described below, in addition to how this sampler improves on those limitations and details of the design, fabrication, deployment, and limitations of the new sampler. The actuating mechanism and packaging of the new sampler is distinct from previous designs and consists of a pressure case that houses sample bottles made of spring-loaded syringes that are sealed and triggered with solenoid valves and electronics to control the valves.

Previous sampler designs and commercially available samplers—A variety of designs for water samplers have been described in the literature and are available commercially. They fall into two general types including those that are submersible and those that are

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deployed on land. Of the submersible samplers, many rely on a variety of ways to capture water within sample chambers. The most common design uses syringes as sample containers that, when actuated, pull water into the barrel of the syringe. In most of these designs, the syringes are attached to a wire line or rod and are activated manually with a messenger (Broenkow 1969; Blakar 1979; Cline et al. 1982) or pneumatically (Heaney 1974). Friederich et al. (1986) automated the tripping of the syringes through the use of a burn wire and an electric timer. Automated sampling using a modified Niskin bottle has also been achieved through dissolution of a magnesium rod, which dissolves 3 h after being deployed in seawater (Sholkovitz 1970). All of these samplers require a mechanical link between the actuator and the sampling tube and thus a substantial mounting frame. Bell et al. (2002) developed a unique style of sampler with an individual sample chamber fitted with a threaded top that is opened and closed with rotary motion driven by a timer-controlled DC motor. Commercially available submersible samplers typically rely on pumps or syringes to fill collapsible bags (McKinney et al. 1997). Many samplers have the capability to preserve samples using a variety of preservatives by either injection into the flow or preinoculation of the sample container. Filters of the samples can be placed in-line of the flow path, or samples can be collected unfiltered.

Samplers that are designed to be deployed on land typically consist of a peristaltic pump that draws water from the sampling port through an ~7 m long polyvinyl tube and discharges the water into one or more sample bottles that are stored in a case onshore. The number of sample bottles ranges to a maximum of 24 and decreases as bottle size increases. The tube moves automatically with a distributor arm to fill bottles sequentially, thereby collecting time series of discrete samples. The tube can be purged before and after taking individual samples to prevent cross contamination of the samples. The sample bottles are housed within a closed case that covers the mechanisms of the sampler and protects the samples from dilution from precipitation or from contamination with external material. The case can be packed with ice to keep samples cool, and the high-end models are refrigerated. The samplers typically are 61 cm high with a diameter of 44 cm and their weight can range from 15 to 73 kg without samples or batteries.

Design of on-shore commercial samplers prevents their application in studying many natural hydrologic systems, such as large rivers, springs, lakes, vadose caves during floods, water-filled caves, or estuaries. Sample containers are open, allowing volatile components to escape and evaporative concentration of solutes during long deployments. These problems are eliminated by using a submersible water sampler, but automatic submersible samplers have been developed only recently (Friederich et al. 1986; McKinney et al. 1997; Bell et al. 2002). Many commercially available oceanographic samplers are designed for deep submergence, some with ratings to more than 6000 m water depth, and consequently can exceed several meters in height and hundreds of kilograms in weight.

Their size, weight, and restriction to noncorrosive and strong materials limit their usefulness in deployment in streams and lakes. The material required for their construction also increases their costs, which might limit the number of samplers that can be deployed during individual projects.

Design of the new sampler—Schematic plans for construction of the sampler are shown in Fig. 1 and photographs of the instrument are shown in Fig. 2. The design is best described as a combination of three separate components: the pressure case, the syringe-solenoid valve system, and electronics. The pressure case is watertight and houses the electronics and samples. The syringe-solenoid valve system provides the force required to collect the samples, acts as the storage containers for the samples, and seals the samples following collection. The electronics package provides a clock and microcontroller to allow sampling by controlling opening and closing of the solenoid valves at preset times. The three components when combined into a single package are approximately 34 cm long and 22 cm in diameter and weigh about 10 kg. It is sufficiently small and light to be deployed by hand from a small boat.

Pressure case—The pressure case is constructed from stock 22 cm outside diameter (OD) schedule 40 polyvinyl chloride (PVC) tubing that is cut square on both ends. The interior corner of the bottom of the tube is cut at a 45° angle (Fig. 1). End caps for the pressure case are constructed from circular pieces of type 1 sheet PVC that have a diameter identical to the outside diameter of the tubular PVC material. The edges of the sheets of PVC are notched to the width of the thickness of the tubular PVC. The top end piece is glued to the tubing case with PVC glue (Fig. 2B). The bottom end cap is fitted with a 0.3-cm diameter O-ring that fills the space created by the interior bottom end of the case. The bottom end piece is held tightly to the tubular section with small latches, and the O-ring wedged between the base and the tube creates a watertight seal (Fig. 1). The pressure case has not been tested to determine its maximum depth of deployment but has not leaked in numerous bench-test deployments. In the current design, the known depth limit is ~20 m, which is controlled by the pressure rating on the solenoid valves of 100 psi. Solenoid valves with higher pressure ratings are available but at greater costs than the valves used for this design.

Syringe-solenoid valve system—The syringe-solenoid valve system consists of ten 60-mL syringes. Each syringe is attached to a single solenoid valve with a Luer Lok fitting. The solenoid valves are 12 volts direct current (VDC) (7 watt) (Kip Inc., part number 241116-03) and have a 5/32-inch (6.16 mm) orifice. The orifice is attached to the base using a 1/8-inch national pipe taper (NPT) standard pipe nipple. Syringes are attached to the solenoid using a 1/8-inch NPT to Luer Lok adapter. The syringes are fitted with springs between the plunger and the body of the spring (Fig. 1). Prior to deployment of the sampler, the syringes are compressed while the solenoid valves are open to allow the air to escape. When the valve is closed, vacuum within the syringe keeps the spring compressed. When

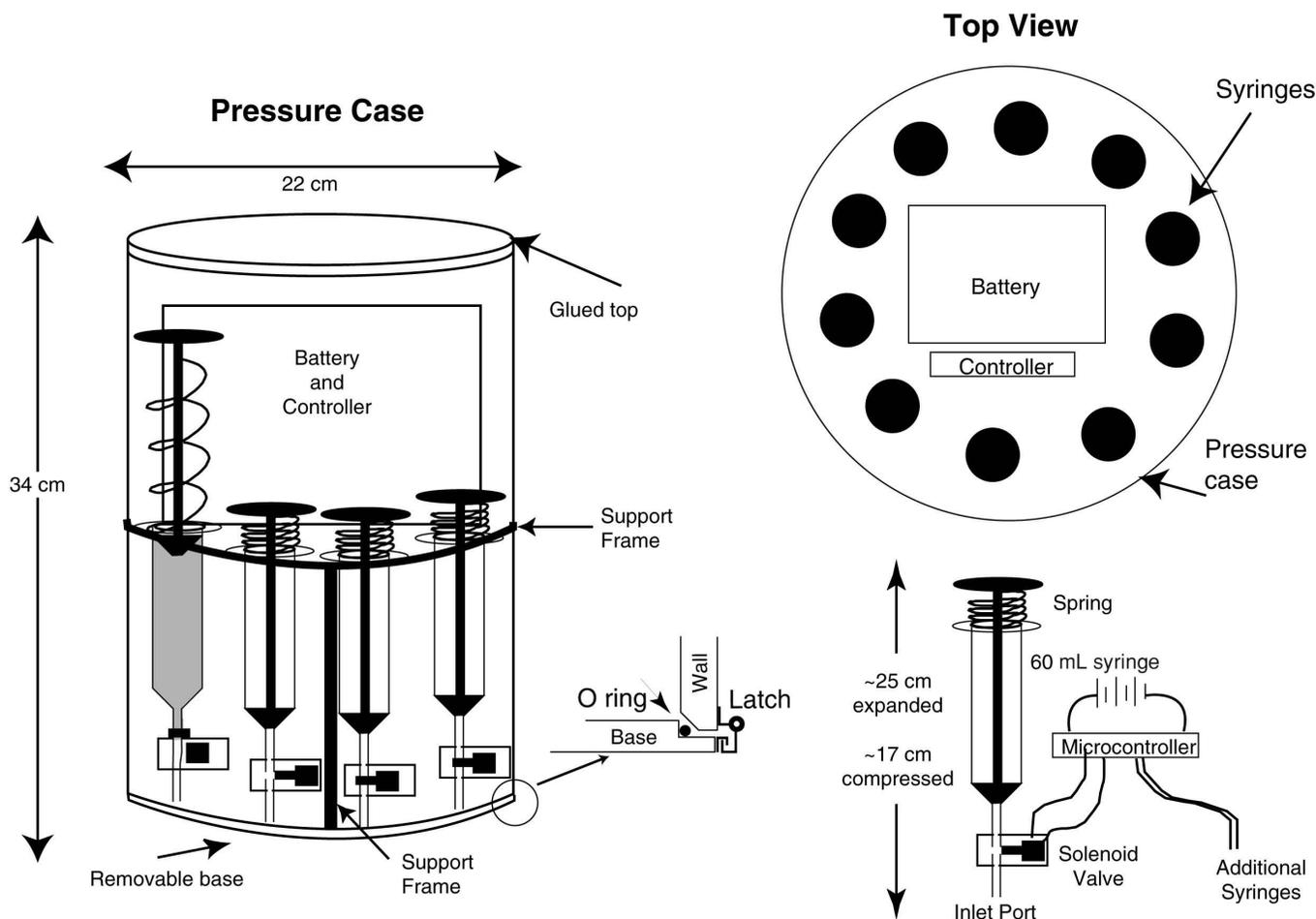


Fig. 1. Schematic diagram of construction of the automatic water sampler. The primary components include the pressure case that contains the sample tubes, solenoid valves, and electronics.

the valve is released, the spring expands and draws water into the syringe. Springs for the sampler were constructed from 26-gauge (1.6-mm) music wire using a spring winder.

The syringes are arranged around the outside diameter of a rack that is connected to the base of the pressure case by a central pedestal (Fig. 2A). The rack consists of flat sheet PVC that is ~0.6 cm (1/4 inch) thick with holes drilled in the sheet that are slightly larger than the barrel of the syringe. The syringes are hung loosely in the holes cut into the rack. When the syringes have filled, they are replaced by twisting them from the Luer Lok fitting and then sliding them upward and out from the holes in the rack. The water remains in the syringe until expelled by depressing the plunger. New, clean, and dry sampling syringes can thus be replaced quickly in the field.

The syringes used for development of the sampler have rubber stoppers, which could contaminate the samples with trace metals and are not gas-tight, thereby possibly allowing gas to diffuse through the plastic during long deployments. Depending on sampling requirements, however, other syringes could be used to alleviate these problems. Syringes constructed entirely of plastic could be substituted to prevent metal contamination

of the samples. Gas-tight syringes made from glass are available commercially, or gas-tight metal syringes could be constructed. These specialty syringes would greatly increase the cost of materials for construction of the sampler.

The syringes used for development of the sampler are 60 mL in size, providing sufficient water for analyses of a wide variety of solutes. For example, major element and nutrient analyses can be measured on a few milliliters of marine and meteoric water by ion chromatography and spectrophotometry, respectively. Isotopic composition of water ($\delta^{18}\text{O}$, δD) can be measured on ~200 μL by gas-source mass spectrometry. Most water has sufficiently high concentrations of dissolved Sr for $^{87}\text{Sr}/^{86}\text{Sr}$ isotope measurements on a few milliliters of water by thermal ionization mass spectrometry. Inductively coupled plasma mass spectrometry is a highly sensitive technique for measuring trace elements and metals, with detection limits commonly in the sub parts per billion range. If additional water is required for particular analyses, more than one syringe can be opened simultaneously, allowing up to 600 mL water sample to be collected by an individual sampler. Several samplers could be deployed at a single location to collect sam-

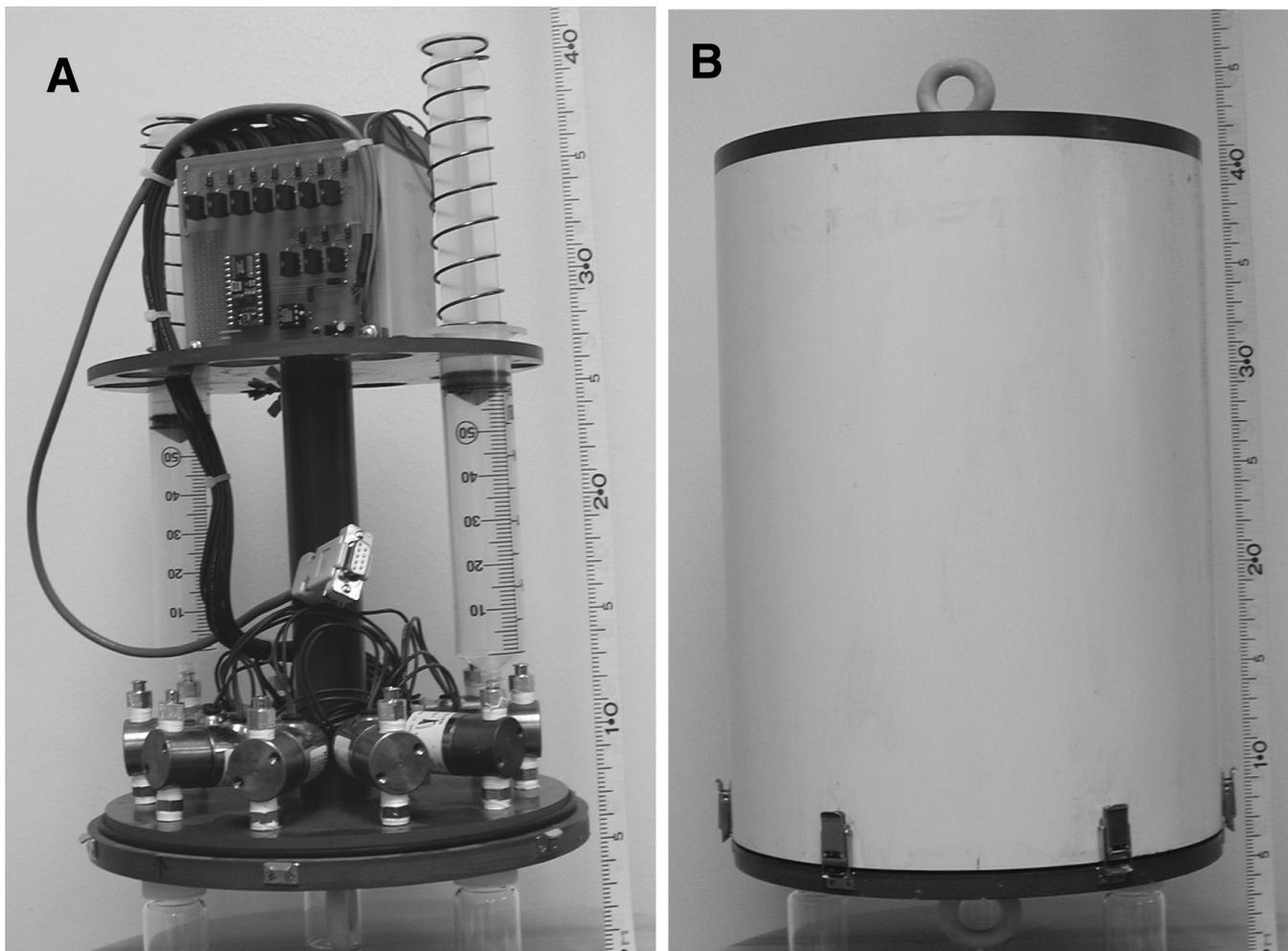


Fig. 2. (A) Interior of water sampler with two syringes installed and fully open. The microcontroller and battery are on top of the support pedestal. Ten solenoid valves are arranged around the base of the sampler. (B) Sampler pressure case showing latches holding the top to the base. Rings in the top and bottom are used to anchor the sampler to the bottom and to daisy-chain several together on one tether. The scale is in centimeters.

ples larger than 600 mL. Alternatively, the size of the pressure case could be increased to allow use of off-the-shelf syringes that are larger than 60 mL, although this increase in size would also increase the buoyancy force and weight of the sampler and likely reduce the strength of the case. Syringes also could be specially fabricated to occupy more of the dead space within the pressure case, thereby capturing larger volumes of water than off-the-shelf syringes (e.g., Fig. 2A).

The design of the sampler allows for both filtration and preservation of the samples. Course (210 μm) screens are attached to the base of the instrument in shallow indentations that are 2.45 cm (1-inch) in diameter and ~ 0.2 cm deep. The filters are held in place using standard 3/8-inch PVC washers (7/16-inch inner diameter and 1-inch outer diameter). The washers are glued into the indentations using standard PVC glue, sandwiching the screens between the washer and the base of the pressure case. The opening in the center of the washer is ~ 1.11 cm (7/16-inch) in diameter, which allows the

screens to be cleaned both manually and by forcing water backward through screen. Filters up to 0.45 μm mesh can be added in line between the solenoid valves and the nipples. These filters can be removed from the nipples following deployment and replaced with new and clean filters. These filters can cause problems, however, by increasing the dead volume between the solenoid and sampler tip and by clogging during deployment in turbid water. Without in-line filters, the small distance between the base of the sampler and the syringe keeps the dead volume to <1 mL, but filters increase this volume by several milliliters.

Preservation of the samples requires placement of a preservative or multiple preservatives in the syringes prior to deployment. The preservative can be added to the tip of the syringe following compression of the spring and before closing the solenoid valve. When the solenoid valve opens, the preservative mixes with the water as it is drawn into the syringe. The type of preservative and volume used (e.g., a bactericide, acid, or combi-

Table 1. Components and estimated costs of one Autosampler II

Component	Cost (\$US)
Pressure case (includes case, O-ring, machining, internal stand)	120
10 Solenoid valves	120
Microcontroller	80
10 Solenoid driver transistors	20
10 Syringes and springs	50
Small diameter tubing (to link syringe, solenoid valve, and filters)	10
Battery	15
Contingency (10%)	42
Total	452

nation) must be determined prior to deployment and will depend on the type of samples being collected.

Electronics—The solenoid valves are operated by a microcontroller coupled to power transistors (MOS-FET) and powered by a small 12 V battery. The microcontroller consists of a Dallas Semiconductor DS1302 Real Time Clock and a Parallax BS2-1C controller with 16 I/O lines and 600 lines of program memory for the controlling software. The software code to control the sampler can be obtained from <http://web.clas.ufl.edu/users/rgthomas/Autosampler/>. The microcontroller has a sleep function and, while sleeping, will draw only 20 μ A. The valves draw \sim 0.5 A when open, and during this time the microcontroller draws an additional 200 mA. Because the valves need to stay open for only \sim 30 s to fill the syringes, the power requirement for the entire system is small. For example, a year-long deployment would require \sim 10 A if all 10 solenoid valves are opened for 30 s each during the deployment. The battery used in the initial construction is a 5 amp-h battery, which has sufficient power for deployment over 1,000 d. The battery weighs approximately 2 kg.

The major sources of weight of the sampler include the battery, solenoid valves, and pressure case. As described here, the sampler weighs \sim 10 kg. The total weight could be reduced with a smaller battery if shorter deployment times were required. The buoyancy of the pressure case is \sim 12 kg, and the 2 kg difference requires a small lightweight anchor to deploy the instrument. Although this sampler is designed only to collect water, it could be modified to also collect in situ measurements of variables, such as pressure (i.e., water depth), temperature (Martin and Dean 2002), and various ions, by modifying the electronics to control ion specific electrodes. Cost for the parts for the sampler is approximately \$450, but if machining of parts, such as the pressure case, is needed, the cost would increase. Construction of the instrument described here required 0.5 h of machining to produce the bevel on the base of the pressure case (Fig. 1). Construction of the case required \sim 8 h and building the circuit board and wiring the instrument took an additional 6 h. The various components needed for construction of the sampler and their estimated costs are listed in Table 1.

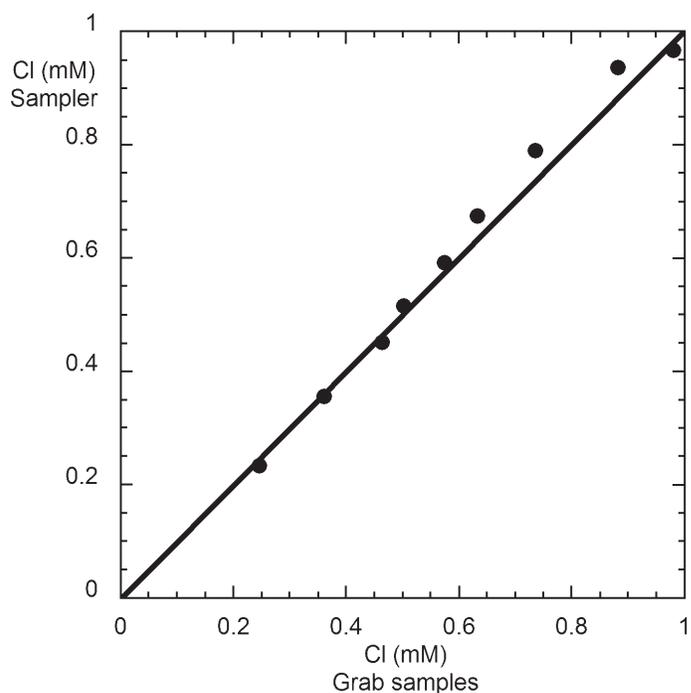


Fig. 3. Correlation plot of Cl concentration (millimoles) of samples collected by hand and samples collected by the SAWS. The line represents a slope of one and indicates that all sample containers open when expected.

Assessment

Several components of the sampler design described here, including the physical robustness of the solenoid-syringe system, the pressure case, and the timing of the electronics, have been bench-tested in several ways. To test the solenoid-syringe system, the springs were kept compressed for several months by depressing the plunger on the syringes and closing the solenoid valves. The syringes remained depressed during the entire experiments, indicating that their vacuum had not been lost. When the solenoid valves were opened at the end of the test, the springs were still sufficiently strong to expand and draw water into the syringes. The empty sampler case was submerged in a water bath on the benchtop for several weeks without leaking.

To test the timing of the electronics, the entire sampler has been deployed in a water bath over a period of 10 d with the microprocessor programmed to open the valves at 0600 h. At 1000 h each day of the test, a NaCl solution of known concentrations was added to the water bath and a sample of the water in the bath was collected by hand. Once all 10 of the syringes had opened, the sampler was removed from the bath, water was extracted from the syringes, and the Cl concentration was measured in water collected by hand and with the sampler. A good correlation of the Cl concentrations in the hand samples and the sampler samples (Fig. 3) indicates that the syringes opened at the time expected. The correlation shown in Fig. 3 also suggests that no water was exchanged between the water bath and the syringes during the deploy-

ment. Deviations from the correlation at elevated Cl concentrations may be caused by incomplete mixing of the saline solution in the water bath, which would allow salt stratification between the bottom of the bath where the samples were drawn into the sampler and the top of the bath where the grab samples were collected.

Discussion

How could the new sampler be used?—Three environments are described below where current sampler designs would be difficult or impossible to deploy or where commercially available samplers are more robust and costly than necessary. The importance of reducing costs of the instruments is that the number that can be deployed and the range of the water body sampled can be maximized. There are likely to be many other applications for a submersible sampler that are not identified here.

Karst aquifers—Karst aquifers are important water sources, supplying nearly 20% of the world's population with water, but their hydrogeology is complicated by three types of porosity, including intergranular porosity of the matrix rocks, fractures, and conduits (White 1969, 1977, 2002). Each type of porosity can provide potable water, but the residence time for water varies between the types of porosity. For example, water in conduits may flow into the aquifer through sinkholes and back to the surface at springs in a matter of days, but water may reside in matrix porosity for years. Consequently, chemical and isotopic compositions of the water will differ among the types of porosity because of variations in the extent of the fluid-solid reactions (Dreiss 1983, 1989a, 1989b). Rapid flow of water into karst aquifers also increases the potential of contamination of karst aquifers (Field 1988, 1993; Andrews 1994; Boyer and Pasquarell 1995, 1996; Katz and Bullen 1997).

Common techniques used to characterize subsurface flow in karst aquifers include observations of changes in natural chemical composition of spring discharge (chemographs). Variations in chemical composition are analyzed using chemographs to identify sources of water within the aquifer (e.g., from conduits, matrix porosity, fractures, or epikarst), its residence time in the subsurface, and mixing with surface water (Pitty 1968; Shuster and White 1971; Shuster and White 1972; Ternan 1972; Hess and White 1988; Dreiss 1989a; Felton and Currens 1994; Padilla et al. 1994; Halihan et al. 1998). Other techniques include qualitative and quantitative dye tracing. These studies are complicated by the need to sample water at high frequency from numerous locations along a single flow path or within a region. Quantitative dye trace studies also require frequent and widely dispersed sampling points (Smart and Hobbs 1986; Smart and Ford 1986). Some sampling for dye trace studies can be accomplished with commercially available samplers, but these tools cannot be used in water-filled cave passages, vadose caves during floods, or large springs, and may be difficult where numerous springs must be sampled simultaneously. Densely spaced sampling for dyes

can be accomplished using activated carbon samplers, but these samples are not quantitative. The sampler as designed would be capable of collecting those samples.

Lakes—Chemical and isotopic compositions of lake sediments are commonly used to reconstruct paleoclimate (Hodell et al. 1995; Curtis et al. 1996; Rosenmeier et al. 2002). These studies assume that other than evaporation and precipitation, the lakes remain closed to groundwater sources. If this assumption is true, carbonate minerals that precipitate in isotopic equilibrium with the lake water should provide a record of the relative amounts of evaporation and precipitation. The assumption of lakes as closed systems could be tested by observing changes in the isotopic composition of the lake water through time in order to compare with its hydrologic and isotopic budgets. In remote areas (e.g., China, South America, Africa, and circum-Caribbean lakes), where much of the paleoclimate work has been accomplished, sampling of lake water over long times (e.g., seasonal) would require automated sampling.

Lake water samples would have to be collected in various areas and depths of the lakes to observe spatial heterogeneity of chemical composition of the lake water and through time to measure the lake's response to changes between wet and dry seasons and from autumnal turnover. Although samples could be collected by hand, it is difficult to arrange sufficient field time to achieve the required sampling density, and on-site volunteers can be unreliable. Automatically collecting water across the lakes and at various depths in the water column requires submerged samplers. The sampler described here could collect these samples by being deployed with anchors and buoys similar to deployment of sediment traps with several individual samplers daisy-chained along a single deployment.

Estuaries—Submarine groundwater discharge appears to be a major part of the hydrologic budget as it enters coastal waters through dispersed seepage along shorelines, as point source seepage through breaches in the confining layer of an underlying aquifer, and as spring discharge (McBride and Pfannkuch 1975; Bokuniewicz 1980; Cable et al. 1996a; Cable et al. 1996b; Moore 1996). Depending on the flux, submarine groundwater discharge may be an important source of dissolved constituents and contaminants such as nutrients, metals, and pesticides, particularly along developed coastlines (Shaw et al. 1998). The extent of the contamination depends on the discharge rate of the water, as well as the concentration of the contaminants, and both are likely to change through time depending on variations in the rates of precipitation, evaporation, and groundwater extraction. It is thus important to have the capability to take frequent samples at widely dispersed locations throughout estuaries.

The rate of groundwater seepage is commonly measured with seepage meters, which are embedded into the sediment of the seafloor and serve to focus the flow through ports attached to the top of the meter (Lee 1977; Sonzogni et al. 1977; Belanger 1992). Flow rates are measured by collecting water over a fixed amount of time as it flows into a sample bag con-

nected to the port, or automatically with heat pulses. The amount of time required to flush the meters depends on the flow rate, but typically requires less than 24 h. Seepage meters recently have been constructed with internal sensors to measure compositions of a variety of solutes or conductivity. Modifying the top of the seepage meter to fit the base of the sampler, similar to designs proposed by Hargrave and Connolly (1978), would allow automated time series collection of the head space water in the seepage meter to address questions, such as whether composition of the seepage water changes seasonally, with changes in precipitation, or over large regions.

Conclusions

Several types of automated water samplers are currently available, both as published designs and commercially. These samplers are designed primarily for sampling from developed environments, from deep marine systems, or require manual actuation to collect the samplers. The advance of the sampler described here stems from increasing sophistication in electronic controllers. The sampler's advantages are its simplicity, small size, low weight, ease in deployment, and low cost. These advantages allow its widespread applications, thereby expanding the range of environments that could be sampled and provide greater access to a wider range of research projects. Although many environments that could be sampled using this sampler are undeveloped (e.g., large rivers, lakes, estuaries, caves), the new sampler could also be used in developed sampling areas that previously would be unavailable to automatic samplers such as within storm water and sewage drains or water supply pipes.

The sampler is fabricated from off-the-shelf parts and thus is limited in its size and configuration. It could be made more compact, or the sample volumes could be increased by custom fabrication of the sample bottles to fit tightly within the pressure case. The sample bottles could also be configured to be exterior to the pressure case, which would then only house the electronics of the sampler. Reducing the size or changing the shape of the pressure case would further reduce the size of the sampler and expand potential environments where it could be deployed. Fabrication of customized parts, however, would increase the cost, and likely would not be effective for production of a limited number of samplers.

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