Philadelphia deploys automatic samplers as soon as possible after a rain event. This sampler features a protective fiberglass enclosure, plastic protective pipe for the water sample line, and a cable for measuring stream depth.

Rain or Shine, 24/7

Philadelphia's mix of water quality monitoring methods ensures around-the-clock data collection during both wet and dry weather

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Like many large cities, Philadelphia is working to improve the water quality of its urban stream watersheds. In accordance with the Clean Water Act and Pennsylvania's Clean Streams Law, the Philadelphia Water Department monitors its urban watersheds to assess their overall chemical and biological health. However, the city found that traditional grab sampling did not sufficiently characterize changes in stream water quality that occur throughout a storm event. Therefore, Philadelphia invested in additional monitoring technology so that it could collect continuous water quality data regardless of the weather conditions.

This monitoring program has been a successful and cost-effective choice for Philadelphia, enabling the city to gather reliable data from its urban streams and dialogue with the state and the U.S. Environmental Protection Agency (EPA) on source control issues.

Restoring Water Quality

Philadelphia's streams are designated as warm-water fisheries and are considered impaired for benthic macroinvertebrates by the state of Pennsylvania. These conditions result from habitat destruction, water quality degradation, sediment loading, and point and nonpoint source pollution. The city maintains National Pollutant Discharge Elimination System (NPDES) permits for stormwater and combined sewer overflow (CSO) discharges to city streams: a municipal stormwater discharge permit and a long-term CSO control plan. Its five urban watersheds are affected by more than 370 major stormwater outfalls and 75 CSO outfalls.

Monitoring water quality helps Philadelphia determine the most effective means for returning these waters to healthy conditions and preventing further impairment. Table 1 (p. 46) provides a list of the water quality parameters that were targeted for monitoring.

Monitoring methods include grab sampling for baseline or dry weather conditions, field meters to collect data at the same time as grab sampling, automated sampling of wet weather events, and data sondes for continuous, unattended data collection. The sondes are portable enough to move from stream to stream to support the long-term monitoring program, which rotates among the different urban streams to assess physical, biological, and water quality characteristics.

Selection of monitoring sites can be complicated. Optimum sites for collecting water samples or installing sondes do not always coincide with optimum locations for stormwater or CSO or tributary influences. Fortunately, Philadelphia's streams, for the most part, are bordered by city parkland, which provides unlimited access for selecting monitoring locations.

Grab Samples

Grab samples are collected midchannel, just below the water's surface, using plastic or glass bottles as required for the parameters of interest (see Table 2, p. 47). Digital cameras are used to document the actual conditions of each sampling location.

Attention to detail has provided for a high level of data quality. Field meters are used to collect *in situ* measurements for pH, water temperature, conductivity, and dissolved oxygen (DO), especially to cross-check with measurements being made back in the lab and with measurements from the data sondes. The pH meter is calibrated in the laboratory, but the calibration check standards are used in the field — closer to the water temperature conditions of 0°C to 30°C — to minimize drift in meter readings. The DO meter is calibrated in the laboratory the day before a field sampling event, on the same sample within 30 minutes, to an air-saturated water sample within ±0.25 mg/L of a Winkler titration. The conductivity meter is calibrated at a temperature as close as possible to 25°C to minimize the temperature compensation error.

Table 1. Parameters Used for Water Quality Monitoring

Parameters	Obtained from data sondes and field meters	Obtained by grab sampling and automated sampling
Fecal coliforms*		X
Escherichia coli		X
Water temperature*	X	
Dissolved oxygen*	X	
pH*	X	
Conductivity	X	
Fluoride**		X
Turbidity	X	X
Alkalinity*		X
Nitrate-nitrogen*		X
Nitrite-nitrogen*		X
Orthophosphate		X
Total suspended solids		X
Total dissolved solids*		X
Total solids		X
Total phosphorus*		X
Total aluminum*		X
Total cadmium*		X
Hexavalent chromium*		X
Total copper*		X
Total iron*		X
Total lead*		X
Total manganese*		X
Total zinc*		X
Calcium		X
Magnesium		X
Total hardness*		X
Ammonia-nitrogen*		X
Total Kjeldahl nitrogen		X
5-day BOD		X
30-day BOD		X

**Parameter is on the Pennsylvania State List of Required Water Quality Parameters.*

***Fluoride was used to assess potential for drinking water input.*

BOD = biochemical oxygen demand.

Automated Samplers

Since the hydrograph of a storm event frequently peaks during the night or early morning when personnel are not available, automated samplers are critical for collecting storm event data. When a wet weather event is anticipated, grab samples are taken to establish a baseline. Then, automatic samplers are deployed as soon as possible prior to the rain event.

The portable, unrefrigerated automatic samplers run on a nickel–cadmium or deep-cycle marine battery. A fiberglass enclosure is secured to protect the sampler at each monitoring site. A level sensor is connected by a 7.6-m (25-ft) cable. Vented, instream pressure transducers monitor relative water depth and trigger the start of sampling when depth increases by a certain increment, such as 0.03 m (0.1 ft). In one stream, this trigger had to be increased to 0.15 m (0.5 ft) because upstream wastewater plant discharges caused a daily rise and fall in stream elevation.

The sampler contains 24 1-L polypropylene bottles. Since each sample event requires three 1-L bottles, each unit can collect a maximum of eight samples. Table 3 (p. 47) shows the required sample volume for each parameter.

Once sampling is initiated, a computer-controlled peristaltic pump provides 1-L samples at preset intervals. The sampler accommodates four user-defined customized sampling programs. Two programs use the level probe to trigger the sampling event, and two are started by clock time. Once sampling is in progress, it often is necessary to reprogram the sampler to better match the storm's hydrograph.

Philadelphia currently takes water level readings every 15 minutes. The sampler turns on the level sensor probe every 5 minutes and records what the level is at the 15-minute mark, then turns off to save battery power. When using the sampler with a continuous power source, the module can average all the readings in the 15-minute time frame and then record the average level reading.

Required equipment for installation includes precut lengths of tubing; polypropylene or stainless steel strainers to keep debris out of the tubing; a toolbox containing a pair of pliers, a wrench, a tape measurer, screwdrivers, and a tubing cutter; an ice chest for samples; and bags of ice to chill the samples in the sampler.

Sampler setup usually takes less than 45 minutes at each site. Staff place each sampler inside its enclosure; attach the battery, tubing, and level module probe cable; calibrate it; take grab samples; program it; and take initial readings. Depending on when a storm event starts, staff may have to visit the sampler periodically to ensure proper collection of samples. When staff visit samplers, they install a new bottle base, place a new bag of ice between bottles, check level readings to determine if the hydrograph is either ascending or descending, and replace the battery. Water level and sample time data are collected with a data logger that is plugged into the sampler. Back in the office, the data can be uploaded to a Water Department computer.

Samplers are left in the field in the protective housing for the season. Pump tubing, discharge tubing, and suction line tubing are changed after every sampling event.

The sampler is programmed to capture samples at critical times on the stream hydrograph, based on analyses of storm event data and stream depth. Sonde deployments in various storms showed that there are two types of storm hydrographs: a more common storm that occurs quickly with a 1- to 2-hour rise to peak flow, and a less common storm that takes 4 to 8 hours to rise to peak flow.

Sample periods, based on a storm's possible hydrograph, include the following:

- **Baseline.** Grab sampling captures the baseline when the sampler is being set up. The sampler is programmed to start sampling once stream water level increases by a set amount above the existing baseline condition.
- **Rising limb.** The sampling program, once triggered, is set to sample every hour, for example, which could take 8 hours to complete a cycle.
- **Descending limb.** Once the peak flow has passed, the sampling is reduced to every 2 hours.
- **Post-storm effects.** Once the storm has ended, the sampler is stopped and grab sampling is done daily to get the post-storm effects, such as for fecal coliforms.

Storm-event sampling generated a large number of samples in a short period of time. For example, one storm might yield a total of 130 samples per parameter for 4 to 5 days from baseline to post-storm effects, for four sample locations, resulting in 2000 separate parameter tests.

Table 2. Grab Sample Volumes

Parameters	Volume Needed
Nitrate-N, nitrite-N, orthophosphate	125 mL
TKN, ammonia-N	500 mL
Total and dissolved solids	1000 mL
Turbidity, alkalinity, fluoride*	500 mL
Total metals w/total phosphorus	60 mL
Dissolved metals	60 mL
Fecal coliform and *Escherichia coli*	100 mL
5-day and 30-day BOD	1000 mL
Total volume collected per site	3345 mL

**Fluoride was used to assess potential for drinking water input.*
BOD = biochemical oxygen demand.
TKN = total Kjeldahl nitrogen.

Data Sondes

Battery-powered data sondes continuously measure pH, water temperature, conductivity, DO, and turbidity. The multiparameter sondes are effective at water temperatures from 5°C below zero to greater than 45°C, at a maximum depth of 9 m (30 ft) for most parameters. In Philadelphia, these are used in a shallow depth of 3 m (10 ft) or less.

Required equipment for sondes includes a calibration cup and probe guard, data logger, 2.4-m (8-ft) field cable, pH probe, DO probe, conductivity and temperature probe, and turbidity probe.

Sondes deployed typically for 2 weeks at a time are programmed for 19 to 21 days, with service scheduled at least every 7 days, to clean and maintain as needed and cross-check the readings with a field meter. In longer deployments, the data collection interval is changed from every 15 minutes to every 30 minutes to save battery life. The calibration of all probes is verified no more than 24 hours before sonde deployment.

Following deployment, all sonde probes are verified with the analysis of check standards in the laboratory. Recalibration of each probe occurs prior to redeployment. Periodic inspections with field meters confirm the reliability of the sonde measurements. Post-deployment validation checks on sonde measurement systems, even after storms, have shown that sondes pass appropriate quality control requirements.

The U.S. Geological Survey suggests inspecting, cleaning, and calibrating the sondes every 3 days or weekly to prevent fouling of sensors and data drift. Periodic cleaning and rinsing of probes has resulted in increased data acceptance.

Sonde positions. In general, it is preferable to locate sondes where samplers are located. Since the samplers need easy and safe access, these sites also make vertical sonde installation and maintenance easier. Philadelphia found that vertically deployed sondes mounted to structures, such as bridges, were safer and easier to maintain — especially during wet weather — and provided more reliable data. Bridges were also good at providing a deeper and more accessible channel.

When deployed in a horizontal position, sondes are hidden and protected in PVC pipe, with holes drilled into the pipe to allow water to flow through it. PVC pipe on the bottom is filled with steel bars packed in plastic bottles with wax, to weigh down the sonde housing yet lift the sonde off the stream

Table 3. Sampler Volumes

Parameters	Sample Volumes
Nitrate-N, nitrite-N, orthophosphate	125 mL
Ammonia-N, TKN	500 mL
Total solids	500 mL
Turbidity, alkalinity, fluoride*	500 mL
Total metals, total phosphorus	60 mL
Fecal coliform and *Escherichia coli*	100 mL
5-day and 30-day BOD	1000 mL
Total volume	2785 mL
Safe volume for automated sampler to collect	3000 mL

**Fluoride was used to assess potential for drinking water input.*

BOD = biochemical oxygen demand.
TKN = total Kjeldahl nitrogen.

Table 4. Sonde Improvements Result in More Reliable DO Data

Year of monitoring	Number of sites in watershed	Total hours deployed (all sites together)	Average percent of hours with accepted DO data	Range in average percent of hours accepted per deployment
2001	6	3290.9	20.2	0.0–42.8
2002	6	4798.4	59.9	43.5–88.3
2003	4	14,626.1	85.8	66.2–93.9
2004	7	21,938.9	79.8	57.7–100.0
2005*	8	34,306.0	93.8	82.9–100.0

**2005 data were collected by sondes in vertical positions.*

DO = dissolved oxygen.

bed. The sonde housing units were designed to maintain the sondes approximately 150 to 200 mm (6 to 8 in.) above the stream bottom, with the probes facing downstream. The sonde housing units were designed to provide a secure and stable docking station for a free flow of water around the sonde's probes while preventing theft, vandalism, and incidental damage.

Sonde performance. Sondes have performed quite well over a 2- to 3-week period in streams of low pollutant loading. However, if they can't be regularly cleaned and maintained, sondes in sites with high levels of suspended solids show erratic, noisy data for DO and pH during and after storm events. In such cases, significant drops in DO, pH, and specific conductance are observed. This problem is particularly common with horizontally deployed sondes.

Prior to a storm event and due to natural biological processes in the stream, sonde pH and DO display diurnal swings. A storm event interrupts this cycling. After the storm event, the diurnal swings slowly return. In some post-storm environments, after a significant loading of suspended solids and silt, the sondes' pH and DO decrease and become fairly flat in variation. In other cases, the decreases in pH and DO are not as severe, and daily variation returns but with less amplitude and more noise. These problems occur because the sonde's housing has become loaded with debris and sediment, and its mesh screen around the probe guard has become caked with solids. Post-storm cleaning of the mesh screen has shown that once the solids are removed, the sonde returns to capturing data representative of the stream.

Field meters are used to measure dissolved oxygen, pH, and other parameters.

The above conditions with DO and pH can also occur in nonstorm periods. Filamentous algae growth and other biological activity have resulted in growth on and within the sonde's housing and on its mesh screen. As a result, DO can decline from daily variations between 8 and 12 mg/L to daily variations of between 1 and 8 mg/L, with more noise. The pH level can also reduce in its daily peak. Hand-held meters will show that the sonde is not measuring stream quality accurately.

Sonde improvements. Philadelphia's improvements to the design and implementation of the sonde housing unit and its deployment were successful, as shown in the increase in accepted DO data from 2001 to 2005 (see Table 4, above). These enhancements included capping the ends of the PVC tubing and drilling holes throughout it so that water could flow freely when sondes are placed horizontally in streams. Horizontally deployed sondes on the stream bottom could not be serviced during a storm event, due to the hazardous conditions; however, vertical deployments allowed servicing at almost any time, except during a major flood. Using more vertical deployments and avoiding horizontal deployments reduced the times that sonde housings and probe guards were clogged during a storm event.

Another improvement was the addition of the self-cleaning sonde, which can measure up to 10 parameters in severe fouling environments for extended periods. The sonde uses a self-cleaning turbidity probe, a DO membrane probe, and a pH probe. These sondes can stay deployed for

28 days in a biofouling environment without periodic cleaning. The DO probe did not fail during most storms but continued to collect data.

Cost Estimates

The total program costs include bioassessment studies of fish and benthic macroinvertebrates, development of reports to the state and EPA, and technical demonstrations for public education. These costs, though, are minor compared to the multi-million-dollar costs for stormwater and CSO controls, and alternative best management practices.

The cost for water quality monitoring and laboratory analysis of a single storm event is approximately $7900. This cost is based on 18 sample sets of the following parameters: total solids, 5-day biochemical oxygen demand, turbidity, alkalinity, fluoride, total Kjeldahl nitrogen, nitrate-nitrogen, nitrite-nitrogen, orthophosphate, total phosphorus, ammonia-nitrogen, fecal coliforms, *Escherichia coli*, total aluminum, total cadmium, hexavalent chromium, total copper, total lead, total manganese, total zinc, total iron, and total hardness. Individual sample costs range from $7 to $40.

For grab sampling — such as for baseline or dry weather monitoring — equipment costs, including pH and DO field meters, are approximately $2500, and annual supplies are about $1250. Labor time is approximately 5 hours per site, including travel time.

To maintain a water quality monitoring station with an automatic sampler and a data sonde, equipments costs are approximately $16,500. Annual supply costs are about $3400, plus $50 per month for standard solutions. Labor time is approximately 31 hours.

Persistence Pays Off

It took several years for the Philadelphia Water Department to establish a reliable system in the city's urban streams. Applications were modified several times. Today, the basic program still uses grab sampling and field meters, but successfully employs vertically deployed, self-cleaning sondes, which are serviced weekly and during storm events. The sonde data acceptance rate is now greater than 80%. Automated samplers in protective housings with piped sample lines complement the sondes by gathering samples during storm events for more detailed laboratory analyses. This successful monitoring program can serve as a model for other jurisdictions that have similar water quality monitoring needs.

The program has generated an abundance of data for modeling and assessments, which put Philadelphia in a very good position to dialogue with the state and EPA on source control issues and the applications of the monitoring results. For instance, grab sampling can either overemphasize or miss an actual water quality problem, making it appear more prevalent than it really is or nonexistent when it really occurs. The data provided through the monitoring program provide a greater level of confidence upon which to make agreements and take action. Monitoring data from one stream were used by EPA and the state to revise and update the model used to generate a total maximum daily load, resulting in more appropriate NPDES discharge limits. Data are also made publicly available for stakeholders and watershed partnership groups to encourage a greater level of involvement in watershed protection.

In general, it is preferable to locate sondes where samplers are located. Here, plastic pipelines connect to a sonde (gray) and sampler (white).

The authors would like to acknowledge the leadership of Geoffrey L. Brock, director of the Bureau of Laboratory Services, and the support of many co-workers in the laboratory. The authors also thank Philadelphia Water Department's Office of Watershed staff, who worked side by side in learning how to successfully apply stream monitoring to Philadelphia's watersheds.

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