6 Monitoring Challenges and Opportunities

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Monitoring is the foundation of water quality management and provides essential information about the resource. Carefully done, monitoring can answer important questions and contribute to a successful NPS watershed project. However, monitoring can also be challenging and offer numerous pitfalls.

Sections 6.1 and 6.2 of this chapter highlight some of the problems that can hinder watershed monitoring efforts from the planning stage through execution. Opportunities to enhance and expand the impact and utility of monitoring data are discussed in sections 6.3 and 6.4.

6.1 Monitoring Pitfalls

Too many watershed monitoring projects have reported little or no improvement in water quality after extensive implementation of BMPs in the watershed. Reasons for this outcome are numerous and varied and may include:

- Mistakes in understanding of pollution sources
- Improper selection of BMPs
- Poor experimental design
- Uncooperative weather
- Lag time between treatment and response

There are numerous ways that a monitoring effort can fail to achieve its objectives. Reid (2001) examined 30 U.S. monitoring programs and classified reasons for failure into design flaws and procedural problems. Design flaws are errors or shortcomings inherent in the monitoring plan that prevent monitoring from obtaining appropriate data, answering fundamental questions, or otherwise achieving its goals. Serious design flaws can doom a monitoring project from the start and no amount of hard work or added resources can salvage it. Procedural problems are problems in execution of a program that can cause even the best design to fail. Unlike design problems, procedural problems can be overcome by applying additional resources, more personnel, better training, or good management.

A list of the top reasons for monitoring failure drawn from Reid (2001) and experience with numerous NPS monitoring projects includes both design and procedural problems.

6.1.1 Design Flaws

- **Inadequate problem identification/analysis.** In some cases, the source of NPS problems is unclear. For example, *E. coli* bacteria can come from livestock, domestic pets, septic systems, or wildlife. Without accurate identification of the pollutant source (*E. coli* in this case), monitoring is unlikely to be able to document a response to treatment effectively.
- **Fundamental misunderstanding of the system.** Effective monitoring of pollutant load or delivery requires an understanding of how the pollutant moves through the watershed. Monitoring in the

wrong place or on the wrong pathway will doom a program to failure. If nitrate-N moves mainly through ground water, for example, monitoring of surface runoff or streamflow is unlikely to yield good results. Similarly, if most suspended sediment at a watershed outlet comes from stream channels and banks, edge-of-field monitoring will not be effective.

- **Inability of the monitoring plan to measure what is needed.** If a sampling station is mis-located – upstream of a critical tributary inflow, for example – samples taken cannot record the pollutant load delivered in that inflow.
- **Insufficient study duration.** Significant lag time between land treatment and water quality response is common (see section 6.2, below). No matter how well-executed, a three-year monitoring program cannot document a response to BMPs if the response takes ten years to become evident because of legacy pollutants or slow watershed processes.
- **Statistically weak design**. As discussed in section 2.4, monitoring design must be carefully selected to achieve program objectives, be they load measurement, change in pollutant concentration, or response to land treatment, notably in the context of weather-driven variability characteristic of NPS pollution. A statistically weak design – such as a single watershed before and after or side-by-side watersheds – cannot control for weather variations and is unlikely to be able to attribute observed changes in water quality to a specific cause.

6.1.2 Procedural Problems

- **Lack of training or enthusiasm of field staff.** If a field technician is unable or unwilling to collect essential data because of lack of knowledge or initiative, critical data may be lost. In extreme cases, individuals can compromise a data record by cutting corners as illustrated in Figure 6-1. A simple time plot of recently obtained laboratory results revealed a pattern that indicated a sampling irregularity, thus triggering an investigation into the cause before further damage could be done.
- **Failure to collect collateral information.** Often, collateral information is required to properly interpret monitoring data. Information on stream stage, for example, may be essential to understand if a water sample was collected on the rising or falling limb of the hydrograph. Failure to record stage at the time of sample collection will greatly reduce the meaning of the sample result.
- **Bad or misunderstood technology.** Modern field or laboratory instruments make it easy to collect a great deal of monitoring data. However, if a field instrument is deployed for long periods without maintenance or calibration, or if a laboratory instrument is not calibrated and tested regularly, the resulting bad data will seriously impair a monitoring program.
- **Failure to evaluate data regularly.** As noted in section 3.10.2 and illustrated in Figure 6-2, it is essential to examine monitoring data frequently to catch problems early. Two dramatic changes in the apparent pattern of TKN concentration were caused by laboratory actions. Replacement of a defective probe in a lab instrument changed the range and sensitivity of the analytical results (point labeled #1). Later a change in lab method significantly raised the detection limit (point labeled #2). These two phenomena required rejection of almost a year of TKN data, but if the problems had not been noted in a data review, serious bias would have been introduced into the monitoring results for a seven-year monitoring effort (Meals 2001).
- **Protocol changes.** Whether in field or laboratory settings, consistent operating procedures are essential to generating consistent monitoring data. Although long-term monitoring programs should strive for consistency in methods and procedures, sometimes it is necessary to replace or upgrade

instruments or change analytical methods. Without careful documentation and extensive comparative analysis, changes in monitoring or analytical procedures can introduce spurious changes in resulting data, changes that do not reflect conditions in the water resource.

- **Personnel change.** Complex monitoring activities – such as those involving GIS or sophisticated laboratory instruments – require a high level of expertise and/or training. Frequent personnel changes can result in loss of such expertise, with a consequent loss of data or of data accuracy, especially if transitions are not managed properly.
- **Lack of institutional integration.** Most watershed monitoring projects involve multiple participants, with responsibility for different activities sometimes spread across several institutions. If the different departments or agencies do not share information or talk to each other regularly, critical information may be overlooked and the monitoring program may suffer.

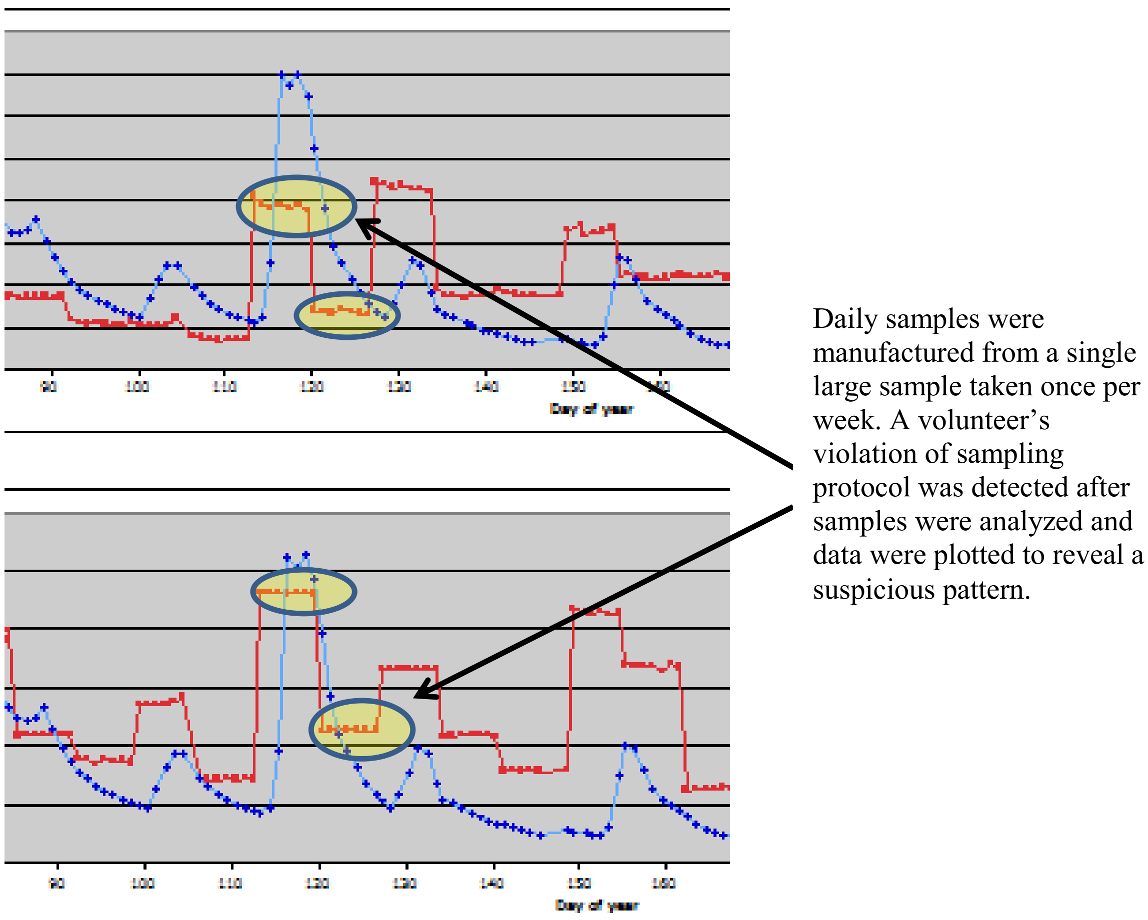

Figure 6-1. Detection of violation of sampling protocol (R.P. Richards, Heidelberg University, Tiffin, OH)

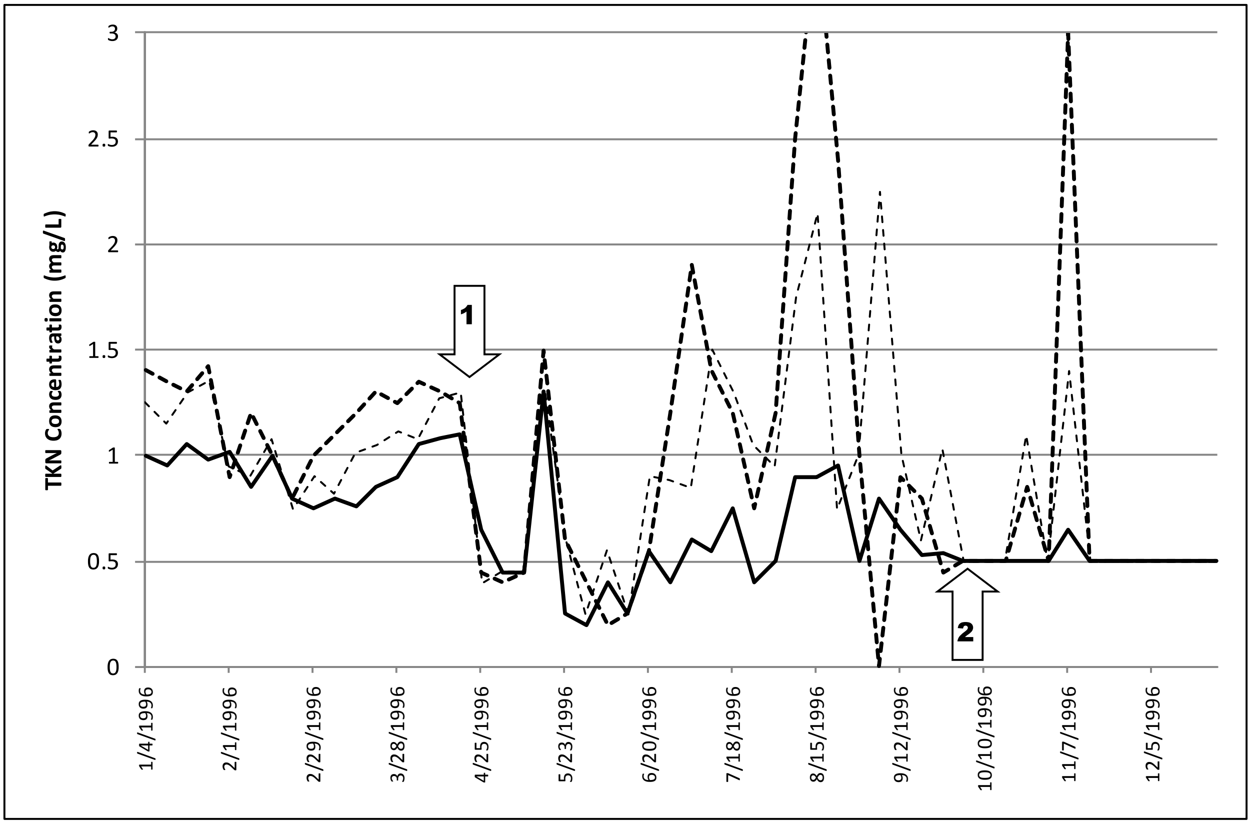

Figure 6-2. Effects of changing (1) a defective probe and (2) a laboratory method detection limit (Meals 2001)

Because design flaws may doom a monitoring project from the start, it is essential to follow the steps in designing a monitoring program discussed in chapters 2 and 3. Procedural problems can be addressed with additional resources, training, and good management during the course of a monitoring program, but such corrections require constant vigilance to identify the problems before they cause too much damage.

6.2 Lag Time Issues in Watershed Projects

One important reason NPS watershed projects may fail to meet expectations for water quality improvement is lag time. Lag time can be thought of as the time elapsed between installation or adoption of management measures at the level projected to reduce NPS pollution and the first measurable improvement in water quality in the target waterbody. Even in cases where a program of management measures is well-designed and fully implemented, water quality monitoring efforts (even those designed to be "long-term") may not show definitive results if the monitoring period and sampling frequency are not sufficient to address the lag between treatment and response. Lag time issues have been explored in detail in a recent review (Meals et al. 2010).

Project management, watershed processes, and components of the monitoring program itself influence the lag between treatment and response (Figure 6-3). Any or all of these may come into play in a watershed project.

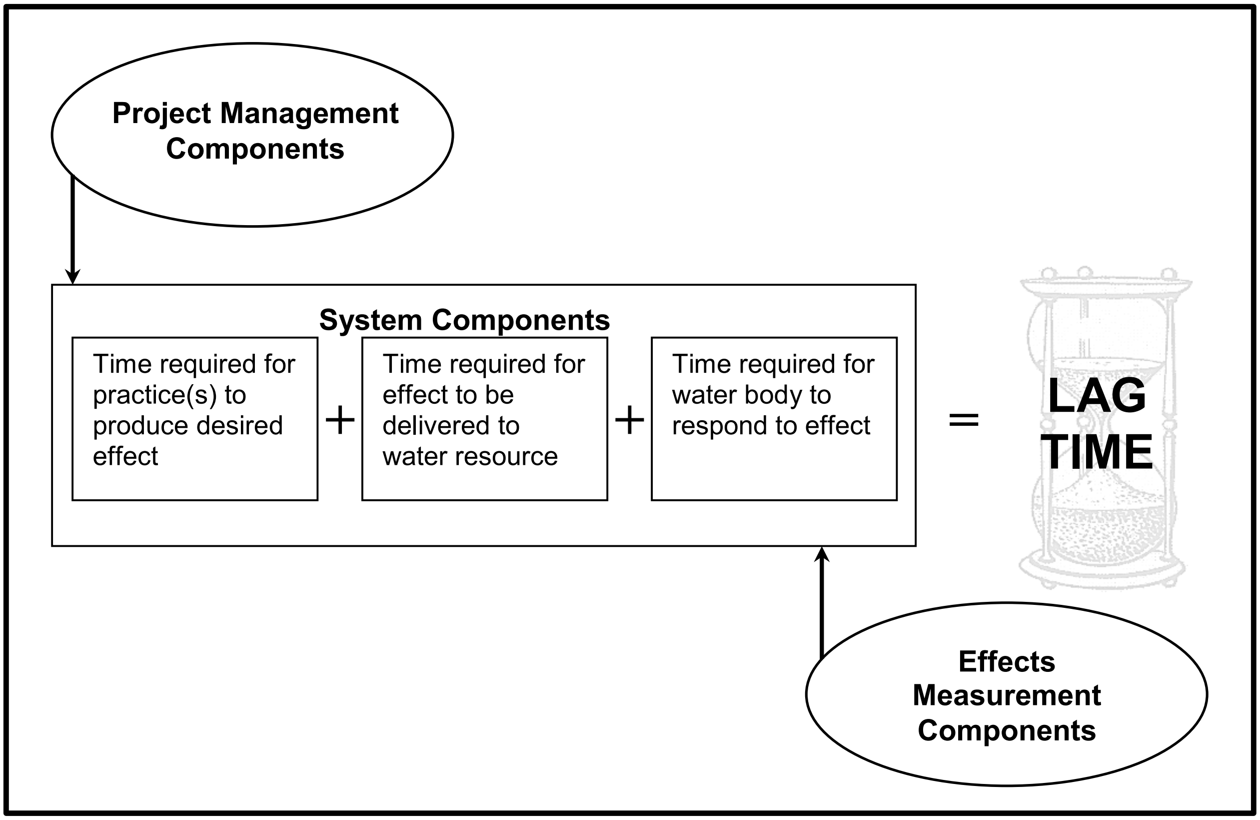

Figure 6-3. Lag time conceptual model

6.2.1 Project Management Components

The time required for planning and implementation of a NPS watershed project often causes the public to perceive a delay between the decision to act and results of that decision. A project may be funded and announced today, but it will be some time before that project will be fully planned and implementation begins. It might even take years, considering the essential time required to identify NPS pollution sources and critical areas, design management measures, engage landowner participation, and integrate new practices into cropping and land management cycles. Although such planning delays are not part of the physical process of lag time, stakeholders will often perceive them as part of the wait for results.

6.2.1.1 Time Required for an Installed or Adopted Practice to Produce an Effect

BMPs are installed in watersheds to provide a wide range of effects to protect or restore the physical, chemical, and biological condition of waterbodies, including:

- Change hydrology
- Reduce dissolved pollutant concentration or load
- Reduce particulate/adsorbed pollutant concentration or load
- Improve vegetative habitat
- Improve physical habitat

The time required for a BMP to be fully installed and become operational influences how quickly it can produce an effect. Some NPS control measures may become functional quickly. Installation of livestock exclusion fencing along several Vermont streams over a three-month period resulted in significant nutrient concentration and load reductions and reductions of fecal bacteria counts in the first post-treatment year as the fences immediately prevented manure deposition in the stream (Meals 2001). However, other NPS management measures, especially vegetative practices where plant communities need time to become established, may take years to become fully effective. For example, in a Pennsylvania study of a newly-constructed riparian forest buffer, the influence of tree growth on nitrate–N removal from groundwater did not become apparent until about ten years after tree planting (Newbold et al. 2009).

Lag time between BMP implementation and reduction of pollutant losses at the edge-of-field scale varies by the pollutant type and the behavior of the pollution source. Erosion controls such as cover crops, contour farming, and conservation tillage tend to have a fairly rapid effect on soil loss from a crop field as these practices quickly mitigate the forces contributing to detachment and transport of soil particles (Nearing et al. 1990). However, the response time of runoff P to nutrient management is likely to be much slower. It may take years to "mine" excess P out of the soil through crop removal to the point where dissolved P in runoff is effectively reduced (Zhang et al. 2004, Sharpley et al. 2007).

6.2.1.2 Time Required for the Effect to be Delivered to the Water Resource

Practice effects initially occur at or near the practice location, yet managers and stakeholders usually want and expect the impact of these effects to appear promptly in the water resource of interest in the watershed. The time required to deliver an effect to a water resource depends on a number of factors, including:

- The route for delivering the effect
  - Directly in (e.g., streambed restoration) or immediately adjacent to (e.g., shade) the water resource
  - Overland flow (particulate pollutants)
  - Overland and subsurface flow (dissolved pollutants)
  - Infiltration groundwater and groundwater flow (e.g., nitrate)
- The path distance
- The path travel rate
  - Fast (e.g., ditches and artificial drainage outlets to surface waters)
  - Moderate (e.g., overland and subsurface flow in porous soils)
  - Slow (e.g., infiltration in absence of macropores and groundwater flow)
  - Very slow (e.g., transport in a regional aquifer)
- Hydrologic patterns during the study period
  - Wet periods generally increase volume and rate of transport
  - Dry periods generally decrease volume and rate of transport

Once in a stream, dissolved pollutants like N and P can move rapidly downstream with flowing water to reach a receiving body relatively quickly. However, sediment and attached pollutants (e.g., P and some synthetic chemicals) can take years to move downstream as particles are repeatedly deposited, resuspended, and redeposited within the drainage network by episodic high flow events. This process can delay sediment and P transport (when attached P constitutes a large fraction of the P load) from headwaters to outlet by years or even decades. Substantial lag time could occur between reductions of sediment and P delivery into the headwaters and measurement of those reductions at the watershed outlet.

Pollutants delivered predominantly in groundwater such as nitrate-N generally move at the rate of groundwater flow, typically much more slowly than the rate of surface water flow. For example, about 40% of all N reaching the Chesapeake Bay travels through groundwater before reaching the bay. Phillips and Lindsey (2003) estimated that N loads associated with groundwater in the Chesapeake Bay Watershed would have a median lag time of ten years for water quality improvements to become evident. Groundwater nitrate concentrations in upland areas of Iowa were still influenced by the legacy of past agricultural management conducted more than 25 years earlier (Tomer and Burkart 2003).

6.2.1.3 Time Required for the Waterbody to Respond to the Effect

The speed with which a waterbody responds to the effect(s) produced by and delivered from management measures in the watershed introduces another increment of lag time. For example, hydraulic residence time (or the inverse, flushing rate) is an important determinant of how quickly a waterbody may respond to changes in nutrient loading. Residence times in selected North American waterbodies range from 0.6 year for Chesapeake Bay to 3.3 years for Lake Champlain to 191 years for Lake Superior to more than 650 years for Lake Tahoe. Simply on the basis of dilution, it will likely take considerably longer for water column nutrient concentrations to respond to a decrease in nutrient loading in Lake Superior than in Chesapeake Bay.

Apparent lag time in water quality response may also depend on the indicator evaluated or the impairment involved, especially if the focus is on biological water quality. A relatively short lag time might be expected between reductions of *E. coli* bacteria inputs and reduction in bacteria levels in the receiving waters because the bacteria generally do not persist as long in the aquatic environment as do heavy metals or synthetic organic chemicals. Such response has been demonstrated in estuarine systems where bacterial contamination of shellfish beds has been reduced or eliminated through improved waste management on the land in less than a year (BBNEP 2008). Improved sewage treatment in Washington, D.C. led to sharp reductions in point source P and N loading to the Potomac River Estuary in the early 1970s (Jaworski 1990). The tidal freshwater region of the estuary responded significantly over the next 5 years with decreased algal biomass, higher water column dissolved oxygen levels, and increased water clarity.

In contrast, lake response to changes in incoming P load is often delayed by recycling of P stored in aquatic sediments. When P loads to Shagawa Lake (MN) were reduced by 80% through tertiary wastewater treatment, residence time models predicted new equilibrium P concentrations within 1.5 years, but high in-lake P levels continued to be maintained by recycling of P from lake sediments (Larsen et al. 1979). Even more than 20 years after the reduction of the external loading, sediment feedback of P continued to influence the trophic state of the lake (Seo and Canale 1999). Similarly, St. Albans Bay (VT) in Lake Champlain failed to respond rapidly to reductions in P load from its watershed. From 1980 through 1991, a combination of wastewater treatment upgrades and intensive implementation of dairy waste management BMPs through the Rural Clean Water Program brought about a reduction of P loads to this eutrophic bay. However, water quality in the bay did not improve significantly. This pattern was attributed to internal loading from sediments highly enriched in P from decades of point and NPS inputs (Meals 1992). Although researchers at that time believed that the sediment P would begin to decline over time as the internal supply was depleted, subsequent monitoring has shown that P levels have not declined over the years as expected (LCBP 2008). Recent research has confirmed that a substantial reservoir of P continues to exist in the sediments that can be transferred into the water under certain chemical conditions and nourish algae blooms for many years to come (Druschel et al. 2005). In effect, this internal loading has become a significant source of P, one that cannot be addressed by management measures on the land.

Macroinvertebrate or fish response to improved water quality and habitat conditions in stream systems requires time for the organisms to migrate into the system and occupy newly improved habitat. Significant lag times have been observed in the response of benthic invertebrates and fish to management measures implemented on land, including in the Middle Fork Holston River project (Virginia), where IBI scores and *Ephemeroptera-Plecoptera-Trichoptera* (EPT) scores did not improve, even though the project accomplished substantial reduction in the sediment, N, and P loadings (VADCR 1997). The lack of increase in the biological indicator scores indicates a system lag time between the actual BMP implementation and positive changes in the biological community structure. This lag could depend in part on the amount of ecological connectivity with neighboring healthier aquatic systems that could provide sources of appropriate organisms to repopulate the restored habitats. In several Vermont streams, the benthic invertebrate community improved within 3 years in response to reductions of sediment, nutrient, and organic matter inputs from the land (Meals 2001). However, despite observed improvement in stream physical habitat and water temperature, no improvements in the fish community were documented. The project attributed this at least partially to a lag time in community response exceeding the monitoring period.

6.2.2 Effects Measurement Components of Lag Time

Watershed project managers are routinely pressed for results by a wide range of stakeholders. The fundamental temporal components of lag time control how long it will take for a response to occur, but the effectiveness of measuring the response may cause a further delay in recognizing it. The design of the monitoring program is a major determinant of our ability to discern a response against the background of the variability of natural systems.

In the context of lag time, sampling frequency with respect to background variability is a key determinant of how long it will take to document change. In a given system, taking *n* samples per year provides a certain statistical power to detect a trend. If the number of samples per year is reduced, statistical power is reduced (the magnitude by which is influenced by the degree of autocorrelation), and it may take longer to document a significant trend or to state with confidence that a concentration has dropped below a water quality standard. Simply stated, taking fewer samples a year is likely to introduce an additional “statistical” lag time before a change can be effectively documented.

6.2.2.1 The Magnitude of Lag Time

The magnitude of lag time is difficult to predict in specific cases and generalizations are difficult to make. A few examples, summarized in Table 6-1, illustrate some possible time frames for several categories of lag times.

Table 6-1. Examples of lag times reported in response to environmental impact or treatment

Parameter(s)	Scale	Impact/Treatment	Response lag	Reference
Sediment	Large watershed	Extreme storm events	8-25 yr	Marutani et al. 1999
Sediment	Large watershed	Cropland erosion control	19 yr	Newson 2007
Chloride	Large aquifer	Road salt	> 50 yr	Bester et al. 2006
NO_3-N	Small watershed	N fertilizer rates	> 30 yr	Tomer and Burkart 2003
NO_3-N	River basin	N fertilizer rates	> 50 yr	Bratton et al. 2004
NO_3-N	Large watershed	Nutrient management	≥ 5 yr	STAC 2005
NO_3-N	Small watershed	Nutrient management	15-39 yr	Galeone 2005
NO_3-N	Small watershed	Prairie restoration	10 yr	Schilling and Spooner 2006
NO_3-N	Small watershed	Riparian forest buffer	10 yr	Newbold et al. 2009
Soil test P	Field	P fertilizer rates	8-14 yr	McCollum 1991
Soil test P	Field	P fertilizer rates	10-14 yr	Giroux and Royer 2007
Soil and runoff P	Plot/field	Poultry litter management	> 5 yr	Sharpley et al. 2007
P	Lake	WWTP upgrade	> 20 yr	Larsen et al. 1979
P	Lake	WWTP upgrade/agricultural BMPs	> 20 yr	LCBP 2008
P, N, *E. coli*	Small watershed	Livestock exclusion	≤ 1 yr	Meals 2001
Fecal bacteria	Estuary	Waste management	< 1 yr	BBNEP 2008
Fecal bacteria	Estuary	Waste management	1 yr	Spooner et al. 2011
Macroinvertebrates	Small watershed	Livestock exclusion	3 yr	Meals 2001
Macroinvertebrates	Small watershed	Mine waste treatment	10 yr	Chadwick et al. 1986
Fish	First order stream	Habitat restoration	2 yr	Whitney and Hafele 2006
Fish	Small watershed	Acid mine drainage treatment	3-9 yr	Cravotta et al. 2009

6.2.3 How to Deal with Lag Time

In most situations, some lag time between implementation of BMPs and water quality response is inevitable. Although the exact duration of the lag can rarely be predicted, in many cases the lag time will exceed the length of typical monitoring periods, making it problematic to document a water quality response. Several possible approaches are proposed to deal with this challenge.

6.2.3.1 Recognize Lag Time and Adjust Expectations

It usually takes time for a waterbody to become impaired and it will take time to accomplish the clean-up. Failure to meet quick-fix expectations may cause frustration, pessimism, and a reluctance to pursue further action. It is up to scientists, investigators, and project managers to do a better job explaining to all stakeholders in realistic terms that current water quality impairments usually result from historically poor land management and that immediate solutions should not be expected.

6.2.3.1.1 Characterize the Watershed

Before designing a NPS management program and an associated monitoring program, investigate important watershed characteristics likely to influence lag time. Determining the time of travel for groundwater movement is an obvious example. Watershed characterization is an important step in the project planning process (USEPA 2008) and such characterization should especially address important aspects of the hydrologic and geologic setting, as well as documentation of NPS pollution sources and the nature of the water quality impairment, all of which can influence observed lag time in system response.

6.2.3.1.2 Consider Lag Time Issues in Selection, Siting, and Monitoring of Best Management Practices

First and foremost, proper BMP selection must be based on solving the problem and ensuring that landowners have the capability and willingness to implement and maintain the BMPs. Lag time can be an important factor in the final design of BMP systems by ensuring that when down-gradient BMPs are installed, they are ready to handle the anticipated runoff or pollutant load from up-gradient sources. In addition, when projects include targeted BMP monitoring to document interim water quality improvements, recognition of lag time may require an adjustment of the approach to targeting the management program. When designing a program for projects that include BMP-specific monitoring, potential BMPs should be evaluated to determine which practices might provide the most rapid improvement in water quality, given watershed characteristics. For example, practices such as barnyard runoff management that affect direct delivery of nutrients into surface runoff and streamflow may yield more rapid reductions in nutrient loading to the receiving water than practices that reduce nutrient leaching to groundwater, when groundwater time of travel is measured in years. Fencing livestock out of streams may give an immediate water quality improvement, compared to waiting for riparian forest buffers to grow. Such considerations, combined with application of other criteria such as cost effectiveness, can help determine priorities for BMP implementation in a watershed project.

Lag time should also be considered in locating management practices within a watershed. Managers should consider the need to demonstrate results to the public, which may be easier at small scales, along with the need to achieve water quality targets and consequently wider benefits at the large watershed scale. Where sediment and sediment-bound pollutants from cropland erosion are primary concerns, implementing practices that target the largest sediment sources closest to the receiving water may provide a more rapid water quality benefit than erosion controls in the upper reaches of the watershed. Where groundwater transport is a key determinant of response, application of a groundwater travel time model before application of management changes could help managers understand when to anticipate a water quality response and communicate this issue to the public. At best, the model will support targeting the application of an initial round of management measures to land areas where the effects are expected to be transmitted to receiving waters quickly. An example of this can be found in Walnut Creek, Iowa (Schilling and Wolter 2007).

It is important to point out that factoring lag time into BMP selection and targeting is not to say that long-term management improvements like riparian forest buffer restoration should be discounted or that upland sediment sources should be ignored. Rather, it is suggested that planners and managers may want to consider implementing BMPs and treating sources likely to exhibit short lag times first to increase the probability of demonstrating some water quality improvement as quickly as possible. “Quick-fix” practices with minimum lag time must be complemented by other needed practices to ultimately yield permanent reductions in pollutant loads.

6.2.3.1.3 Monitor Small Watersheds Close to Sources

In cases where documentation of the effects of a management program on water quality is a critical goal, lag time can sometimes be minimized by focusing monitoring on small watersheds, close to pollution sources. Lag times introduced by transport phenomena (e.g., groundwater travel, sediment flux through stream networks) will likely be shorter in small watersheds than in larger basins. In the extreme, this principle implies monitoring at the edge of field or above/below a limited treated area, but small watersheds (e.g., < 1500 ha) can also yield good results. In the NNPSMP, projects monitoring BMP programs in small watersheds (e.g., the Morro Bay Watershed Project in California, the Jordan Cove Project in Connecticut, the Pequea/Mill Creek Watershed Project in Pennsylvania, and the Lake Champlain Basin Watersheds Project in Vermont) were more successful in documenting improvements in water quality in response to change than were projects that took place in large watersheds (e.g., the Lightwood Knot Creek Project in Alabama and the Sny Magill Watershed Project in Iowa) in the 7- to 10-year time frame of the NNPSMP (Spooner et al. 2011).

Monitoring programs can be designed to get a better handle on lag time issues. Monitoring indicators at all points along the pathway from source to response or conducting periodic synoptic surveys over the course of a project will identify changes as they occur and document progress toward the end response. Supplementing a stream monitoring program with special studies can help project managers understand watershed processes, predict potential lag times, and help explain delays in water quality improvement to stakeholders. In the Walnut Creek (IA) watershed, no changes in stream suspended sediment loads were documented, despite extensive conversion of row crop land to prairie and reductions in field erosion predicted by RUSLE (Revised Universal Soil Loss Equation). This was explained largely by a 22-mile stream survey showing that streambank erosion contributed more than 50% of Walnut Creek sediment export (Spooner et al. 2011).

6.2.3.1.4 Select Indicators Carefully

Some water quality variables can be expected to change more quickly than others in response to management changes. As documented in the Jordan Cove (CT) NNPSMP Project (1996–2005), peak storm flows from a developing watershed can be reduced quickly through application of stormwater infiltration practices (Clausen 2007). NNPSMP projects in California, North Carolina, Pennsylvania, and Vermont demonstrated rapid reductions in nutrients and bacteria by reducing direct deposition of livestock waste in surface waters through fencing livestock out of streams (Spooner et al. 2011).

Improvements in stream biota, however, often come beyond the time frame of many watershed-scale monitoring efforts, but a number of NNPSMP projects have documented success with biological monitoring. As noted in section 6.2.1, Meals (2001) found that the benthic invertebrate community in Vermont streams improved within 3 years in response to livestock exclusion practices, but improvements in the fish community were not documented. Whitney and Hafele (2006) noted improvements in the fish community within two years of a habitat restoration effort, and Cravotta et al. (2009) documented the gradual return of fish to streams within a few years after treatment to neutralize acid mine drainage.

Despite these successes, many other watershed-scale projects have failed to document improvements by monitoring macroinvertebrates and fish. This may simply argue for a more sustained monitoring effort to document a biological response to land treatment. Failing that, however, selection of indicators that have relatively short lag times where possible will make it easier (and quicker) to demonstrate success. Simple numbers of macroinvertebrates, for example, may respond before more complex community indices show change. See chapter 4 for additional details and illustrative case studies on biological monitoring approaches.

6.2.3.1.5 Design Monitoring Programs to Detect Change Effectively

Monitor at locations and at a frequency sufficient to detect change with reasonable sensitivity. Assess background variability before the project begins and conduct a minimum detectable change analysis as described in section 3.4.2 to determine a sampling frequency sufficient to document the anticipated magnitude of change with statistical confidence (Spooner et al. 1987, Richards and Grabow 2003). Although lag time will still be a factor in actual system response, a paired-watershed design (Clausen and Spooner 1993, King et al. 2008), where data from an untreated watershed are used to control for weather and other sources of variability, is one of the most effective ways to document water quality changes in response to improvements in land management. If a monitoring program is intended to detect trends, evaluate statistical power to determine the best sampling frequency for the project. See Meals et al. (2011) and section 7.8.2.4 for additional information on trend analysis.

Target monitoring to the effects expected from the BMPs implemented, in the sequence that those effects are anticipated. For example, when the ultimate goal is habitat/biota restoration in an urban stream, if BMPs are implemented first that will alter peak stormflows, design the monitoring program to track changes in hydrology. After the needed hydrologic restoration is achieved, monitoring can be redirected to track expected changes in channel morphology. Once changes in channel morphology are documented, monitoring can then focus on assessment of habitat and biological community response. Response of stream hydrology is likely to be quicker than restoration of stream biota and would therefore be a valuable—and more prompt—indicator of progress.

6.3 Integrating Monitoring and Modeling

Monitoring and modeling are the primary tools for assessment of NPS watershed projects. By providing essential data about the resource, water quality monitoring has long been the foundation of water quality management. Monitoring can, however, be expensive and technically challenging and requires careful design and execution to achieve objectives. Modeling, on the other hand, is indispensable in evaluating alternative scenarios and in forecasting water quality over time. Modeling is also technically demanding, and application of a model in the absence of observed data can contribute to legitimate skepticism and uncertainty about model results that can compromise the utility of modeling for watershed management. To meet the demands of future watershed programs, it is essential that we integrate the strengths of both tools.

6.3.1 The Roles of Monitoring and Modeling

Both monitoring and modeling have distinctive roles to play in watershed projects. In many cases these roles are complementary, but in some cases one tool is used as a substitute for the other for various reasons including budgetary constraints.

6.3.1.1 Monitoring

Monitoring plays many key roles in watershed projects:

- Identify and document water quality problems and impairments

- Assess compliance with water quality standards and other regulations
- Establish baseline conditions
- Provide credibility to project planning
- Provide data to support modeling
- Document water quality change
- Assess program or project effectiveness
- Provide information for adaptive management
- Inform stakeholders
- Contribute to behavior change by documenting actual watershed conditions

Monitoring can provide fundamental knowledge about the generation, fate, and transport of NPS pollutants. Monitoring data provide hard evidence of water quality impairment and represent the best evidence of water quality restoration. When successful, monitoring can effectively document water quality response to land treatment, e.g., reductions in nutrient and sediment loads resulting from livestock exclusion in Vermont (Meals 2004) and reductions in nitrate loading to streams from prairie restoration in Iowa (Schilling and Spooner 2006).

Water quality monitoring also presents important challenges in watershed projects. Over the past decades, many projects have failed to show water quality response through monitoring. Such failure can be attributed to shortcomings in both design (e.g., failure to measure what is needed, inadequate sampling frequency) and execution (e.g., failure to evaluate data regularly, inadequate staff training, poor institutional integration) (Reid 2001). As noted throughout this guidance, monitoring must be conducted under appropriate objectives with a statistical design that can meet those objectives. Monitoring must be conducted at a frequency adequate to meet objectives (e.g., to document change) and for an adequate duration (e.g., to overcome lag time). Water quality monitoring must be executed effectively, with careful attention to procedural issues like collection of collateral information, regular data evaluation, and institutional coordination.

6.3.1.2 Modeling

Modeling also plays a number of critical roles in watershed projects:

- Provide initial estimates of flow and pollutant loads
- Link sources to impacts and evaluate relative magnitudes of sources
- Identify critical areas for management
- Predict pollutant reductions and waterbody response to management actions
- Support informed choices among alternative actions
- Analyze cost-effectiveness of alternatives
- Address issues of lag time in system response to treatment
- Guide monitoring design
- Help build knowledge of natural processes and response to treatment

- Provide opportunities for collaborative learning and stakeholder involvement

Modeling can forecast future response to alternatives too numerous or time-consuming to monitor effectively. Modeling provides the means to assemble, express, and test the current state of knowledge and point the way for future investigations. Model applications for watershed evaluation range from the simple to the very complex. An Oklahoma project used SIMPLE (*Spatially Integrated Models for Phosphorus Loading and Erosion*) to identify high-risk P sources in the Peacheater Creek watershed to design a land treatment plan (Storm et al. 1996). A recent Vermont project used SWAT (*Soil and Water Assessment Tool*) to identify critical source areas for NPS P in a large agricultural watershed (Winchell et al. 2011). National CEAP Cropland Studies in the Upper Mississippi River Basin (USDA-NRCS 2012), the Chesapeake Bay region (USDA-NRCS 2011a), and the Great Lakes system (USDA-NRCS 2011b) used SWAT and other models to quantify the effects of conservation practices currently present on the landscape in the regions and to project potential benefits that could be gained by implementation of additional conservation treatment in under-treated agricultural acres.

Modeling also presents significant challenges in watershed projects. Some data are always required – for model parameterization, calibration, and validation – and inadequate supporting data can significantly degrade model performance. Technical and financial resources are required for modeling that may be difficult to assemble and sustain. Modeling may be impaired by inappropriate or outdated information (e.g., soil surveys, use of Curve Numbers), or by lack of fundamental understanding of how agroecosystems or urban stormwater processes function. The credibility of model application may be threatened by lack of appropriate algorithms for simulating conservation or urban stormwater management practices and by failure to adequately analyze uncertainties associated with model results. Model results nearly always require analysis and interpretation to be useful; failure to provide such support can lead to justifiable skepticism about model results. The Chesapeake Bay model, for example, has been criticized for overstating environmental achievements in contradiction to monitoring data (GAO 2005, Powledge 2005). Disputes or misunderstandings over pollutant loads simulated by the SPARROW model in the Mississippi River Basin have generated economic and political conflict over source identification and choices of alternatives for remediation (Robertson et al. 2009).

6.3.2 Using Monitoring and Modeling Together

Clearly, monitoring and modeling are not mutually exclusive and can be better integrated in watershed protection and restoration projects. Each tool has its own strengths and weaknesses and neither can by itself provide all the information needed for water quality decision-making or program accountability. Integration of monitoring and modeling should address these elements:

Use the strengths of both tools.

- Monitoring is the best tool for project evaluation, but modeling simulations and extrapolations can play an important role in projecting whether project success is likely.
- Modeling can provide guidance on where and how the on-the-ground monitoring is best conducted.
- Modeling is better than monitoring for comparing numerous scenarios and extrapolating effects into the future.
- Data collected through monitoring are essential for calibration and validation of models, and for establishing credibility for modeling-derived information.

- The validity of model application and the type of questions that are addressed must be corroborated by watershed stakeholders.
- Models are underutilized for collaborative learning purposes. Their use within collaborative frameworks must be promoted to incorporate feedback from stakeholders while demonstrating how decisions at the field-scale affect the environment.

Begin with project objectives and design the monitoring-modeling program to do what can be done well to meet those objectives.

- Begin with a clear set of objectives. Determine if the objectives need to be quantitative (e.g., reduce N load by 40%), if they need to incorporate time frames and scales for which accountability is needed (e.g., reduced N load at a tributary mouth or at each HUC-12), and if there is a need to attribute changes to activities on the land (e.g., in response to implementing specific management measures at a specified level).
- Establish a clear set of evaluation objectives. Define the specific questions to be answered with monitoring (measure N load reductions with a minimum detectable change of 20%) and with modeling (measure and project N load reductions within ±15% of actual loads). Incorporate the needed time frames and scales within the objectives, and ensure that monitoring and modeling objectives are complementary. For example, the monitoring objective might be to measure N load reductions with a minimum detectable change of 20% in select smaller watersheds within 10 years and assess with an MDC of 30% long-term N load trends at mouths of larger watersheds and the state line. The evaluation objective for modeling might be to estimate and project N load reductions within 15% of actual loads in select smaller watersheds within 10 years and estimate and project within 15% of actual long-term N load trends at mouths of larger watersheds and the state line. Address uncertainty at the outset and include uncertainty in all monitoring and modeling reporting.
- Select a model based on project needs – models selected solely by cost or convenience before setting objectives are unlikely to be satisfactory.
- Create a monitoring program that will collect the number and frequency of samples that are required to provide useful information – monitoring designs based solely on budget may yield data that cannot serve project objectives.

Select the appropriate designs.

- Establish the monitoring design(s). Address overall experimental design (e.g., long-term trend, upstream-downstream) and specify the elements of monitoring scale, sample type, station locations, sampling frequency, collection and analysis methods, land use/land treatment monitoring, and data management (see chapters 2 and 3).
- Select the modeling approach. Determine which model(s) to use, input data requirements and availability, model testing locations and procedures, and procedures for output analysis. Make certain that adequate technical skill and support are available for the selected approach.

Pay attention to source data.

- Availability of data at consistent scales and of known quality is essential to an integrated monitoring-modeling effort.
- Spatially- and temporally-explicit land treatment and agricultural management data are necessary for both water quality monitoring and watershed modeling.

- Identify common needs of monitoring and modeling. Share precipitation, land use, land treatment, and other data. Use monitored flow and water quality data to calibrate and validate the model(s).

Evaluate the suitability of both monitoring data/programs and proposed model(s) for the project in the project planning stage, before a project is funded and underway.

- Evaluate existing and planned monitoring data for quality, consistency, and suitability for project purposes.
- Evaluate candidate watershed models for applicability to watershed characteristics, technical competence, and resources necessary to apply and support modeling in the project.
- Verify that important watershed characteristics (e.g., claypan soils) and conservation and stormwater management practice functions can be adequately represented in the selected model.

Integrate data analysis and reporting.

- Combine systems for discharge calculations, loads calculated from monitoring data, and land use/land treatment data.
- Link monitoring data to a GIS framework used for modeling.
- Provide for compatibility between monitoring data and model(s) to permit efficient use of monitoring data for model calibration and validation.
- Facilitate analysis of small-scale monitoring and modeling to develop input parameters for large-scale model application(s).

Include a documentation plan for both monitoring and modeling.

- Use a formal Quality Assurance Project Plan (QAPP) to guide and document all aspects of the monitoring and modeling efforts.
- Lay out the purpose of model application and the justification for the selection of a particular model.
- Document the model name and version and the source of the model.
- Identify and document model assumptions.
- Document data requirements and sources of data sets to be used.
- Provide estimates of the uncertainty associated with modeling and monitoring results, particularly when they are used to quantify the environmental benefits of practices.

Develop a communication strategy. Control expectations from the beginning by addressing monitoring and modeling uncertainty explicitly. Avoid overly optimistic projections.

Be aware of potential differences in precision and accuracy of modeling results vs. monitoring data. Monitoring data may be used to identify trends or changes in water quality (see sections 7.7 and 7.8); such trends are identified in the context of statistical confidence, based largely on the characteristics of the monitoring program (see MDC, section 3.4.2). Model predictions, however, may show changes in water quality without the benefit of statistical trend analysis and thus suggest very small trends that cannot be verified by monitoring data. Monitoring data may, for example, support a MDC of 20% for phosphorus concentration, while a model may predict a 7% reduction. This situation is not necessarily contradictory, but calls for a bit of realistic caution in application and interpretation of model results.

Finally, in practical terms, project water quality monitoring and watershed modeling activities must be closely coordinated so that information from each effort can be collected, shared, and combined at appropriate times to meet project goals. Preliminary model runs to identify critical subwatersheds, for example, can also be used to help select monitoring station locations. Similarly, water quality data that are analyzed in a timely fashion as described in section 3.10.2 are more likely to be available at the right time for model calibration and validation.

6.4 Supporting BMP and Other Databases

6.4.1 General Considerations

Monitoring is often performed to develop a better understanding of BMP effectiveness, characterize reference conditions over broad geographic areas, determine effluent characteristics, or address other purposes not directly related to problem assessment or watershed project evaluation. In some cases this monitoring can be done in conjunction with problem assessment or project evaluation to maximize the return on resources expended, but this monitoring is often done separately.

The basic steps presented in chapters 2 and 3 should also be applied to development of monitoring plans in support of BMP and other databases. Some of the specifics may not apply, however, such as watershed characterization or monitoring of meteorological variables in cases where urban stormwater BMPs are assessed in a laboratory setting. Pollutant transport mechanisms and pollutant source activities may be of little interest in monitoring designed to establish reference conditions. Still, the focus on objectives must be the driving force behind all monitoring design.

For new databases, decisions need to be made regarding the types and quality of data that will be included. Development of a QAPP (see chapter 8) is an important first step in defining data needs and data quality expectations for the database.

When monitoring to support existing databases, it is essential that data requirements are reviewed and understood before the monitoring plan is developed to ensure that suitable data will be collected. For example, those managing the International Stormwater BMP Database have developed guidance with recommended BMP monitoring protocols that are directly related to requirements of the database, and have established a recommended protocol for evaluating BMP performance (Geosyntec and WWE 2009). This database is described in section 6.4.2.

Databases may have specific requirements for monitoring designs (e.g., above/below), sampling type (grab or composite), sampling frequencies, specific variables (e.g., EPA Method 365.4 for total P), and other monitoring details, as well as requirements for reporting information on the study conditions and features. For example, it may be required that designs for BMPs are reported in accordance with industry standards, or that a specific level of detail be reported for soils or crops. All of these requirements need to be reviewed and understood before monitoring begins.

Data format, approaches to data analysis, and data transmittal requirements may also be specified. Questions and issues associated with these requirements need to be addressed up front to prevent problems later.

The single most important step to take when monitoring in support of database development is for those performing the monitoring to communicate with those managing the databases to ensure that monitoring, data analysis, reporting, and data management requirements are understood and that the proposed monitoring plan is suitable before monitoring begins.

6.4.2 International Urban Stormwater BMP Database

The International Stormwater BMP Database (www.bmpdatabase.org/) is a database of over 530 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance, and other study-related publications. The overall purpose of the project is to provide scientifically sound information to improve the design, selection, and performance of BMPs. Data obtained from BMP studies are expected to help create a better understanding of factors influencing BMP performance.

The database is focused on field studies of post-construction, permanent BMPs (International Stormwater BMP Database 2013). Data entry requirements are specified in a user's guide (WWW and Geosyntec 2010). Options for BMPs include structural BMPs, non-structural BMPs, low-impact development sites, and composite BMPs. Monitoring results may include precipitation, flow, water quality, and settling velocity.

Guidance is provided on approaches to determining BMP performance using concentrations, loads, and volume reductions (Geosyntec and WWW 2009). Comparison of the average value of the Event Mean Concentrations (EMC) or storm loads for the outlet as compared to the inlet is emphasized. Examining the cumulative distribution of each of the outlet and inlet storm EMCs allows for more detailed examination of the efficiency at different inlet loadings. This approach, the Effluent Probability Method (Strecker et al. 2003, Erickson et al. 2010), is described in more detail in section 7.7.2.

The database structure and contents may be downloaded from the project website and used solely for the following purposes (International Stormwater BMP Database 2013):

- Research and analysis related to BMP performance and costs, characterization of urban runoff, characterization of receiving water impacts, and characterization of the ability of BMPs to meet water quality goals or criteria.
- Use of database structure and/or data entry spreadsheets to track performance data for regional, state, watershed or local purposes or for subsequent upload to the International Stormwater BMP Database.

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