CRITICAL SOURCE AREA IDENTIFICATION AND BMP SELECTION: SUPPLEMENT TO WATERSHED PLANNING HANDBOOK

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SUMMARY

Effective application of agricultural, urban, and other nonpoint source (NPS) best management practices (BMPs) requires that these measures are properly planned, sited, and sized for implementation. An important aspect of the planning process is the identification of critical source areas (CSAs). Implementing these BMPs and other complementary measures (e.g., in-lake treatments funded through sources other than Section 319 funds) in CSAs is a key part of meeting targets set by Watershed Management Plans (WMPs) or Total Maximum Daily Loads (TMDLs), which ultimately lead to achieving water quality and quantity goals and objectives, including the restoration and protection of designated beneficial uses of waters of the U.S.

This document is intended to help watershed project teams define CSAs where appropriate BMPs and BMP systems will be implemented to achieve water quality goals in the most efficient manner possible. Effective determination of CSAs will usually result in identification of smaller areas within a watershed that contribute a disproportionate amount of pollutants of concern or contribute otherwise in a disproportionate manner to the identified water resource problems of concern. This document was written to support targeted, cost-efficient implementation of practices and measures to meet water quality goals in a timely manner. This document is not a technical how-to manual with step-by-step procedures or solutions for all watersheds, but is rather intended to inform such site-specific actions carried out at the local level. The background information, methodology, examples, and overview of data sources and tools are intended to document progress made in this area and provide a platform for enhancing the state of the art. While the document is based on a rigorous review of past and current efforts to define and treat CSAs, approaches and tools continue to evolve and practitioners will need to track new developments.

This supplement describes a procedural methodology for targeting CSAs and appropriate BMPs and BMP systems intended to guide implementation strategies that will meet watershed goals and objectives. The technical approach presented here relies on a data-driven assessment of factors to identify critical locations where there is a high probability of pollutant delivery to receiving waters. This is a results-based approach for selecting both appropriate BMPs and BMP systems, and the necessary management tools to support or promote BMP implementation in those critical locations. The methodology involves:

- Establishing restoration/protection priorities
- Describing connections from transport pathways to potential sources
- Estimating the relative contribution from these sources
- Identifying CSAs and BMP performance expectations and implementation opportunities

- Targeting CSAs and appropriate BMPs and BMP systems where implementation will be most effective
- Monitoring progress and adjusting as needed in an adaptive management approach

A broad range of data sources and tools is described to help watershed managers carry out these tasks at varying levels of cost and complexity. A multi-disciplinary approach is recommended for identifying CSAs and selecting BMPs, BMP systems, or other management measures to take advantage of the knowledge, data, and expertise of all stakeholders in the watershed. Appropriate identification of CSAs should help ensure that BMPs and BMP systems are fully implemented within a specified timeframe.

A key component of the process to identify CSAs is *establishing priorities* that will address documented problems/concerns relative to water quality management plan goals and objectives (Figure 1). Locations are targeted where load reductions are most needed based on watershed conditions. Information used to target priority locations of concern includes water quality data, flow data, biological assessments, and habitat evaluations.

After priorities are established, the methodology focuses on *describing connections* that link problems to potential sources. By focusing on key pathways, source categories are highlighted that may contribute to water quality problems. This approach allows potential source areas to be delineated using mapping tools designed to help evaluate key factors such as land use information and management measures and practices (e.g., urban development, crop production).

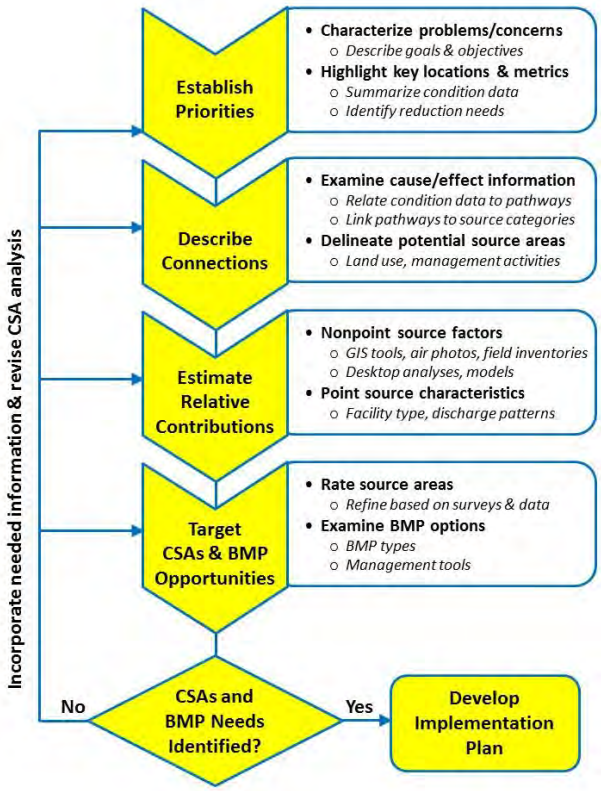

Figure 1. Process overview for identifying critical source areas and BMP opportunities.

Estimating relative contributions sets the stage for narrowing the list of potential source areas to those locations where BMP implementation will be most effective in achieving water quality goals and objectives. These estimates can range from narrative descriptors (e.g., high, medium, low) derived from aerial photo analysis or field inventories to quantitative values developed from desktop screening tools or models. Although this is supplemental NPS program guidance, point source contributions also must be accounted for in the analysis.

Targeting CSAs and BMPs ensures that implementation resources are applied to appropriate management practices and are directed to those areas contributing disproportionally to problems and concerns. Source area ratings are refined based on a more detailed analysis of survey information and available data. CSA targeting also examines BMP options, including both practice types and management tools. It must be understood that CSA identification can be an iterative process. Choices and decisions are not always clear, often resulting in a need to compile additional data or revisit information examined in earlier steps. *Monitoring* of plan implementation will produce the information needed to make adjustments in an adaptive management approach.

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FOREWORD

This document is written for both experienced watershed practitioners and those new to the field. It is assumed that experienced practitioners have basic knowledge of watershed planning, data sources, and analytic tools.

1. Overview

1.1 Background

Achievement of water quality goals, either for protection or restoration, requires that problems and threats are assessed correctly, causes and sources are accurately identified, appropriate pollutant reduction targets and restoration needs are determined, proper BMPs and other measures are selected, and a requisite level of implementation of treatment is accomplished within a specified timeframe. Environmental response to plan implementation will be most rapid when the right BMPs and other measures are planned, sited, sized, and implemented in those areas that have the greatest influence on water quality and related problems. In addition, such a targeted approach may often increase the cost efficiency when considering dollars spent on BMP costs per pound of pollutant reduction (Lazarus et al., 2014). It should be noted, however, that BMP costs are only part of overall costs, and other costs such as labor for communicating with landowners in targeted areas may not be insignificant.

The examples presented here are helpful for documenting lessons learned because they illustrate general patterns that have been observed broadly. Findings based on modeling need to be considered with some caution because these tools generally employ assumptions regarding unit area pollutant loads, general BMP effectiveness, and other factors and conditions that vary within and across watersheds. While the degree to which these assumptions result in an "average" rather than a true site-specific outcome will differ with each specific application, it is important to keep in mind that these tools are most helpful in providing a starting point for further investigation and analysis, rather than for reaching definitive and actionable conclusions about a specific watershed or treatment plan.

How Large is a Watershed?

Level	HUC[1] Digits	Name	Unit Size (Average or Range)	
			Square Miles	Acres
1	2	Region	177,560	113,638,400
2	4	Subregion	16,800	10,752,000
3	6	Basin	10,596	6,781,440
4	8	Subbasin	703	449,920
5	10	Watershed	63-391	40,000-250,000
6	12	Subwatershed	16-63	10,000-40,000

[1]Hydrologic unit code (e.g., HUC10 is a 10-digit HUC)
Source: Virginia DCR (2017a)

Lesson: Targeted Approaches Improve Efficiency in Achieving Water Quality Goals

Diebel et al. (2008) used statistical simulations to evaluate program efficiency gains that could be realized by geographically targeting and aggregating pollution control efforts involving multiple complementary BMPs associated with riparian buffers in Wisconsin. Specifically, the authors examined total pollution reduction and proportion of watersheds improved for four geographical allocation approaches (aggregated/targeted, aggregated/random, dispersed/targeted, and dispersed/random). The approaches differed in two ways: (1) whether the effort is aggregated within certain watersheds or distributed without regard to watershed boundaries (dispersed), and (2) whether the effort is targeted toward the most highly phosphorus (P)-polluting fields or is distributed randomly with regard to field-scale P pollution levels. They found that the approach combining targeting of the most highly P-polluting fields with aggregating within certain watersheds is the most efficient approach to achieving measurable stream water quality changes. For example, with effort on only 10 percent of a

model landscape, 26 percent of the total P load would be reduced and 25 percent of watersheds significantly improved.

Doody et al. (2012) argued that targeting programs at CSAs for P control could significantly improve the environmental efficiency and cost effectiveness of proposed mitigation strategies in Irish watersheds. They proposed a tiered approach for identifying CSAs in recognition of the knowledge of P export at the field scale, limited availability of site-specific data and tools, and difficulty associated with accurate identification of CSAs at the catchment scale due to the increasing complexity of hydrological processes at larger scales. This approach would use catchment-scale tools in conjunction with field-by-field surveys to reduce uncertainty and provide a more practical and cost-effective method of delineating CSAs in a range of catchments.

Lesson: Critical Source Area Identification and Treatment are Essential to Success

As noted by Ghebremichael et al. (2012), studies have long reported that the success of NPS pollution control efforts depends on the ability to properly identify, target, and remediate critical areas of pollution (Maas et al. 1985, McDowell et al. 2001, Meals et al. 2010, Pionke et al. 2000, Sharpley et al. 2006, Walter et al. 2000, Weld et al. 2001). In a review of the thirteen watershed-scale (8- to 12-digit HUCs) projects funded under the National Institute of Food and Agriculture–Conservation Effects Assessment Project (NIFA-CEAP), Osmond et al. (2012a) concluded that CSAs must be identified and conservation practice implementation should be targeted to those areas to achieve water quality goals. By identifying CSAs, managers can prioritize BMPs to better protect water quality and reduce pollutant loads (Meals et al. 2012).

Watersheds must also be of manageable size to enable accurate CSA delineation and design of effective treatment plans that can result in measurable water quality improvements in timeframes of 5 to 15 years or so. For example, Coffey et al. (1992) concluded that smaller watersheds of less than 30,000 acres should be selected for agricultural nonpoint source projects that last from 6 to 15 years because problems in these areas can be more readily identified, are easier to treat, and respond more rapidly to treatment. The U.S. Environmental Protection Agency (USEPA) adopted this watershed size recommendation in its guidance for the Section 319 National Nonpoint Source Monitoring Program (NNPSMP) (USEPA 1991). Of 28 projects, only 6 had watersheds exceeding 30,000 acres, and 5 of those conducted their monitoring efforts in areas smaller than 30,000 acres.

Lazarus et al. (2014) concluded that application of their Minnesota-based Watershed Nitrogen Reduction Planning Tool for optimizing agricultural BMP selection to reduce the nitrogen (N) load from the highest contributing sources and pathways in a watershed will help planners develop the most achievable and cost-effective approach for reducing watershed N loads. The spreadsheet-based N planning tool optimized selection of nine different agricultural BMPs for reducing the N load from the highest contributing sources and pathways in a watershed.

Using the Soil and Water Assessment Tool (SWAT) to assess the effects of conservation practices on reducing sediment and nutrient loads at field and watershed scales in the St. Joseph River watershed, Her et al. (2016) concluded that application area, field-scale effectiveness, and placement of the practices are equally critical in achieving watershed-scale water quality improvement. They found that implemented practices were not focused in the areas of the watershed where they were most needed, thus reducing the watershed-level load reduction efficiency in the largely agricultural watershed. At the same time, however, they acknowledged that the effectiveness of conservation practices is site-specific. This complicates the process of identifying optimal placement of practices for watershed-scale load reductions and water quality improvement when using models.

Lesson: Major Sources of NPS Pollutant Loads Are Disproportionately Distributed

Nowak et al. (2006) applied the concept of disproportionality to investigate why NPS loading to a lake had not changed even though commonly recognized social drivers (e.g., manure management) had changed significantly. They examined interactions of social and biophysical variables (e.g., daily P load) at different spatial and temporal scales and found that limited occurrence of inappropriate behaviors in vulnerable biophysical settings resulted in disproportionate environmental impacts. For example, an inappropriate land-management practice may not result in significant environmental impacts in a well-buffered biophysical setting (e.g., over-grazing of pastures distant from any waterbodies), whereas an appropriate practice may contribute unusually large pollutant loads in a highly vulnerable biophysical setting (e.g., construction meeting all erosion control requirements but occurring in an area with P-enriched soils). It is important, therefore, to closely examine the site-specific relationships between behavior (e.g., adoption of BMPs) and environmental processes (e.g., source area pollutant loadings) within the watershed to refine CSA delineations rather than accepting conclusions based on relationships between measures of social and biophysical processes (e.g., enrollment in conservation programs versus cropland erosion rates) that are aggregated at a coarser scale (both spatial and temporal). A few outliers within a watershed—including cases of good management in an area with exceptionally high risk of pollutant delivery (e.g., P enriched soils from previous land use)—can contribute disproportionately to overall pollutant loads.

Giri et al. (2016) targeted CSAs in the suburban Neshanic River watershed of New Jersey by combining delineation of hydrologically sensitive areas (HSAs) with high pollution producing areas of watersheds. Location of HSAs was based on a soil topographic index derived from a wetness index and soil transmissivity, whereas high pollution producing areas were determined by using SWAT to estimate unit-area pollution loads for sub-areas of the watershed. CSAs for each pollutant (sediment, nitrogen, and phosphorus) were then identified based on the HSAs and the sub-areas with high unit-area pollution loads. The resulting CSAs for sediment, nitrogen, and phosphorus represented only 0.2, <0.1, and 1.2 percent of the watershed, respectively.

White et al. (2009) used SWAT to identify and quantify sediment and total phosphorus loads originating from CSAs in six priority watersheds in Oklahoma. Within these six watersheds, 5 percent of the land area yielded 50 percent of sediment and 34 percent of the phosphorus load. In watersheds dominated by agriculture, the worst 5 percent of agricultural land contributed, on average, 22 percent of the total agricultural pollutant load. Pollutant loads from these agricultural CSAs were more than four times greater than the average load from agricultural areas within the watershed.

Lesson: CSAs Should be Determined Through A Systematic Process

Lessons learned from the U.S. Department of Agriculture's (USDA's) Rural Clean Water Program (RCWP) included recognition of the need to target land treatment to CSAs where BMPs are likely to most improve and protect the water resource (USEPA 1990). Targeting criteria identified for ranking CSA treatment needs included:

- Magnitude of the pollutant source
- Distance to the water resource
- Location, type, and severity of the water resource impairment or threat
- Type of pollutant
- Present conservation [i.e., management] status
- On-site evaluation

Based on lessons learned from the RCWP, USEPA incorporated CSA identification within its Section 319 NNPSMP guidance (USEPA 1991). Specifically, the guidance stated:

The critical area definition should reflect the magnitude of source, pollutant delivery to the waterbody, relationship of the pollutant to use impacts, treatability, and relative treatment costs. Such an approach will help project planners select treatment areas that will provide necessary pollution control and greater likelihood of water quality improvements…Critical area treatment goals should be specified in quantitative terms. Management practice systems should be specifically tailored to the sources and pollutants they will be used to control.

Several lessons regarding CSA delineation were learned from the NNPSMP. The following findings are based on reviews of project reports and direct communication with project scientists and managers:

- **Stream Restoration**: In urban settings such as the Waukegan River (IL) project area where storm runoff is the major contributor to degraded stream habitat, CSA definition that includes the drainage area as well as the damaged stream reaches would seem appropriate (Tetra Tech 2006d). Failure to manage storm runoff and water quality could result in temporary rather than long-term improvements in stream biology.
- **Urban Runoff**: The Jordan Cove (CT) project identified activities associated with construction and residential land use, as well as traditional erosion controls, as critical source activities (Tetra Tech 2006e). The entire area of the small treatment watershed (4.2 acres) was considered part of the CSA to be treated.
- **Phosphorus Loading**: Findings from the Missisquoi Bay Study (IMBSB 2012) included that CSA targeting for P hotspots should be implemented at two spatial scales: subwatershed and farm scale. A tiered approach was also recommended by Doody et al. (2012).

Lesson: Data and Tools Appropriate for CSA Determination Range from Simple to Complex

The data and tools needed to identify CSAs will vary depending on watershed characteristics (e.g., sources and pathways for different pollutants) and water quality goals, and project budgets will influence which of these resources can be obtained or used. The National Water Quality Evaluation Project developed a generalized framework for integrating problem identification, information gathering, data management, and project assessment into a logical conceptual system for agricultural nonpoint source water quality projects in support of early USEPA/USDA joint watershed programs such as the RCWP (NCSU 1981). A key element of this framework is identification of CSAs and the need to collect increasingly refined information when moving from general qualitative assessments (e.g., watershed scale, general pollutants, general land uses) to more detailed characterization of sources and pollutant pathways (e.g., field or small catchment scale, specific pollutants, specific sources).

Data sources and tools of varying complexity were used by the 21 RCWP and 28 Section 319 NNPSMP projects. The following examples illustrate the types of data and tools used by these projects in addressing a range of pollutants and pollutant sources:

- **Turbidity:** To address turbidity problems, the Highland Silver Lake RCWP project in Illinois targeted natric soils with 2 percent slope, fine particle size, and high erodibility, and non-natric soils with 5 percent slope, high erodibility, and proximity to the stream system to refine the CSA (USEPA 1990).
- **Pesticides and Nutrients:** The Bayou Bonne Idee RCWP project in Louisiana addressed turbidity, sedimentation, and pesticide problems by targeting cropland adjacent to the water body (USEPA 1990). Cotton growing on silty soils had the highest priority because the fields were close to waterbodies, intensively cultivated, and receiving both pesticides and nutrients.
- **Phosphorus:** The St. Albans Bay RCWP project in Vermont addressed eutrophication in St. Albans Bay by targeting areas nearest major water courses or the bay where major nonpoint sources of phosphorus

were present (USEPA 1990). Computer models were used to estimate total phosphorus and sediment loads from alternative management scenarios.

- **Bacteria:** The Tillamook Bay RCWP project in Oregon targeted land with high-priority dairies to address high fecal coliform levels and sediment loading to Tillamook Bay (USEPA 1990). Priority dairies were identified via a computer program that calculated fate and movement of bacteria through dairy operations and manure management practices (Moore et al. 1992). The factors used in the mass-balance model included number of cows in the herd; type, capacity, and management of waste storage unit; bacterial die-off in storage; waste application method and rate; bacterial die-off on the surface; precipitation; infiltration of water and bacteria; and transport (Moore et al. 1983).
- **Nitrate:** In Minnesota, the Garvin Brook RCWP project expanded their 30,720-acre watershed to include 15,800 additional acres that served as a major groundwater recharge area for wells in the original watershed (Wall et al. 1993). The project shifted from an early focus on surface water to an emphasis on groundwater quality after it was discovered that nearly one quarter of 80 sampled wells had nitrate-nitrogen levels above 10 mg/L. In addition, monitoring and hydrogeologic investigations conducted early in the project revealed that the ground and surface watersheds had different boundaries, and that some of the groundwater data they had collected prior to the project reflected conditions 30 years earlier and was therefore not useful in evaluating the impact of the RCWP project.
- **Erosion Control** (NNPSMP Projects – Lake Pittsfield, Illinois; Sycamore Creek, MI; Whitewater Creek, MN)**:** Critical area delineation at the watershed scale was performed using a range of approaches even within the same project, including stream proximity and direct observation of visible sediment-contributing areas (MI), sediment yield estimates (MI and MN), and watershed models (MN) (Tetra Tech 2006b). The Lake Pittsfield project reported that visual observation alone is not always adequate to identify CSAs. The relationships among in-stream sediment loads, upland sediment delivery, and stream bank erosion are often not fully understood when projects develop their implementation plans.
- **Grazing Management/Riparian Restoration** (NNPSMP Projects – Long Creek Watershed, NC; Pequea and Mill Creek Watershed, PA; Lake Champlain Basin Watersheds, VT)**:** Several approaches were used for CSA delineation at the watershed scale, including conservative (protective) assumptions based on land-based or water quality information at hand (Pequea/Mill Creek), watershed models (Long Creek), streamwalks and habitat assessments (Vermont), and field surveys (Long Creek and Vermont) (Tetra Tech 2006c). Streamwalks and habitat surveys were very useful and less expensive than modeling efforts in Vermont. The Pequea/Mill Creek project, however, showed that visual observation alone may not be adequate to identify CSAs when pollutants such as nutrients or other runoff constituents are part of the problem.
- **Animal Waste Management/Nutrient Management** (NNPSMP Projects – Warner Creek, MD; New York City Watershed, NY; Long Creek, NC; Peacheater Creek, OK; Totten and Eld Inlets, WA; Otter Creek, WI)**:** A whole-farm planning process (NY), watershed models (NC, OK, WI), streamwalks and habitat assessments (OK), and field surveys (MD, WA) were used for CSA delineation (Tetra Tech 2006a). For example, eight of nine dairy operations and cropland on two of the eight dairies were designated as CSAs in the Otter Creek watershed; the USDA-Natural Resources Conservation Service (NRCS) model BARNY was used to determine which barnyards were critical. Although the Oklahoma project was initially focused on downstream nutrient problems, data collected by the project showed that streambank erosion and bedload sediment were more critical problems in the monitored watersheds.

In support of their tiered approach to identify CSAs, the Missisquoi Bay Study parameterized (i.e., determined the representation of physical effects by simplified parameters) an updated version of SWAT, with a Variable Source Area function (SWAT-VSA) to enable SWAT to more accurately identify CSA sectors in the Vermont portion of the watershed (IMBSB 2012). This “strategic analysis” was followed by a more refined “tactical analysis” in which they

applied precise, site-specific input data and better spatial resolution to improve identification and ranking of CSAs at the farm-scale. The SWAT-VSA model was built to include agricultural field boundaries in the model structure, thus providing a common unit area for both the strategic and tactical analyses. SWAT model calibration and validation confirmed that the model met or exceeded all pre-established performance targets. Calibration and validation routines were examined for hydrology, sediment load, and phosphorus load. In addition to identifying CSA sectors, the SWAT-VSA model was used to compare a CSA-targeted approach for BMP implementation with a random implementation of BMPs across the landscape. In addition, a simpler, less data-intensive GIS-based analysis was performed to identify CSAs in the watershed using available remote sensing imagery and known land uses in the watershed. These results were then compared to CSAs identified in the SWAT-VSA-based CSA analysis. Overall, the results were similar for agricultural, dense urban, and forested areas of the watershed. For the strategic analysis, an enhanced hydrologic network was used to identify hydrologic features of the watershed that could connect sources of phosphorus to the tributary network. Hydrologic proximity rankings and total phosphorus load rankings were assigned across the entire network. CSAs were then ranked based on these two metrics. Trained field staff visited 19 sites identified by the model as either CSAs or not CSAs, and confirmed 17 of the model assessments. At the farm-level scale, a conventional 100-cow dairy farm in Franklin county was selected for tactical CSA analysis.

Buchanan et al. (2013) proposed a NPS index based on runoff travel times from saturated variable source areas to the natural stream network. Their travel-time phosphorus index (TTPI) was applied to a 9,400-acre agricultural watershed in central New York and shown to yield realistic, spatially explicit predictions of critical phosphorus loading areas and routing pathways. Runoff travel time is only one of many factors that could be considered for this type of index, and in some cases, travel time is difficult to assess. Still, when resources are limited, projects should focus on the factors most important to an accurate delineation of their specific CSA, as was done in this study. While this approach may be too complex for many watershed project teams, the study is helpful in demonstrating the need to consider the potential role of small artificial drainage networks when delineating CSAs for some pollutants. They found that without the inclusion of roadside and agricultural ditches, many of the more CSAs would be miscategorized as low risk zones. In this watershed, they found that the ditches usually ran perpendicular to the slope and were directly adjacent to un-buffered agricultural fields with high TTPI values. In contrast, the natural streams were generally located in valleys that were buffered on both sides by riparian vegetation.

Lazarus et al. (2014) describe a spreadsheet-based watershed N planning tool for optimizing selection of nine different agricultural BMPs for reducing the N load from the highest contributing sources and pathways in Minnesota watersheds. The spreadsheet contains data for 68 HUC8 watersheds and for the state as a whole. It was used to inform the development of Minnesota's Nutrient Reduction Strategy for the Mississippi River Watershed.

Michigan guidance for developing watershed plans emphasizes the value of following up CSA determination with an inventory of the CSA to refine the list of pollutants, sources, and causes (Brown et al. 2000). They recommend performing visual inventories by walking, driving, or canoeing the CSA. Advantages noted for visual inventories include gaining the most accurate picture of what is occurring in the watershed, familiarizing involved individuals with the watershed, and providing an opportunity to introduce the watershed project to riparian landowners. Disadvantages include the time involved and the large volume of data required (e.g., photographs, maps) and developed (e.g., land use inventories, streambank condition, discharge pipes in the stream). They contrast this, however, with modeling and GIS approaches that, while appropriate in many cases, may require substantial data input and highly skilled individuals.

Lesson: Implementation Levels in CSAs Must be High to Achieve Water Quality Goals

A simple scatter plot of data from the RCWP (Figure 2) indicates that, six years into the program, treatment of at least 70 percent of the CSA may be required to achieve measurable water quality results. It should be noted that a range of factors, including how precisely the CSAs were defined, the types and extent of BMPs implemented, the specific pollutants addressed, the water resource type, and the quality of the water quality monitoring program influence the likelihood of measuring water quality improvement. Still, the plot shows that no project with treatment levels below 60 percent had measured water quality improvements. It is to be expected that as CSA definition becomes more precise, the minimum required treatment should increase as only essential pollutant sources remain. The only exception to this pattern would pertain to situations where an error margin or treatment inefficiency was factored into CSA delineation.

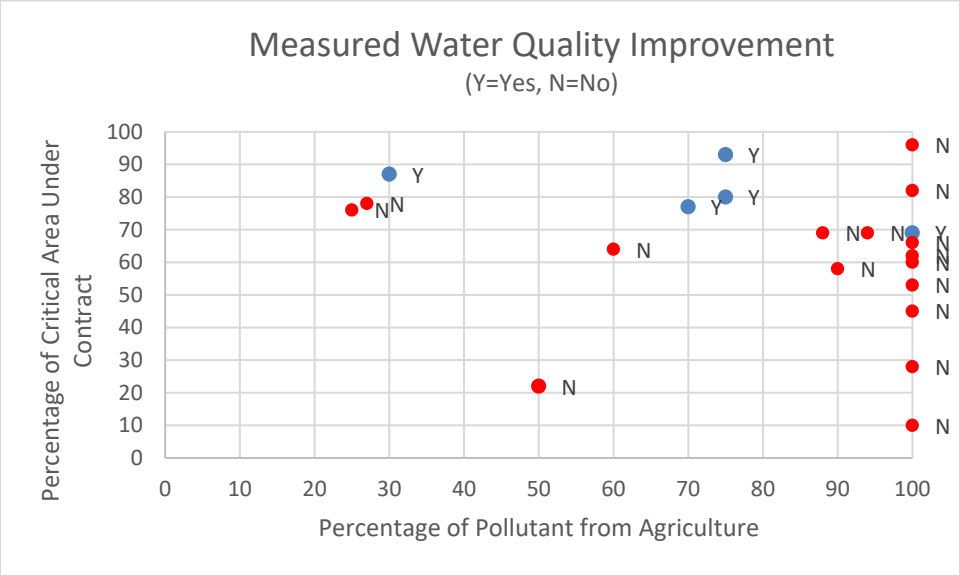


Figure 2. RCWP water quality results as a function of CSA treatment level and agricultural contribution (data compiled by Piper et al., 1989).

Lesson: Treatment Practices are Best Applied in a Systems Approach

Findings from the RCWP indicated that systems of two or more BMPs were required to effectively control NPS pollution from most CSAs in agricultural settings (NCSU 1992). This knowledge was incorporated in USEPA's Section 319 NNPSMP guidance (USEPA 1991) in the following manner:

> *It is important that the watershed plan takes into account the combined effects of the management measures that will be installed. For example, a project with suspended solids problems should assess the importance of all major sediment sources and anticipate potential shifts in the importance and/or magnitude of those sources as implementation of management practice systems proceeds. A project focused on cropland erosion control, but having inadequate streambank stabilization, may fail to improve water quality because suspended sediment delivered in runoff from highly eroding lands may, after application of erosion control practices, be replaced by suspended sediment from scoured stream bottoms and banks.*

USDA is currently exploring the use of a conservation management systems (CMS) approach for treatment, defined as (USDA-NRCS 2017):

> *A CMS is a group of conservation practices that support one another. When implemented, the CMS has a synergistic effect - the positive impact is greater than if the practices were implemented alone. Many individual conservation practices need the support of other practices to be successful. For example, a filter strip will soon be rendered ineffective if sheet and rill erosion is not controlled up stream of the filter area. The filter strip will fill with sediment and lose its ability to absorb nutrients.*

Two basic CMS practice combinations have been established for situations with and without manure (Table 1):

Table 1. Practices in conservation management systems (USDA-NRCS 2017)

Nutrient Management Conservation System	Waste Utilization Conservation System
Conservation Cropping System (328)	Conservation Cropping System (328)
Residue and Tillage Management (329, 345, 346)	Residue and Tillage Management (329, 345, 346)
Cover Crops (340)	Cover Crops (340)
Buffer Strips (327, 386, 390, 393)	Buffer Strips (327, 386, 390, 393)
Nutrient Management (590)	Structure for Water Control (587)
	Drainage Water Management (554)
	Nutrient Management (590)
	Waste Utilization (633)
	Waste Transfer (634)
Numbers in parentheses are USDA-NRCS conservation practice standard numbers.	

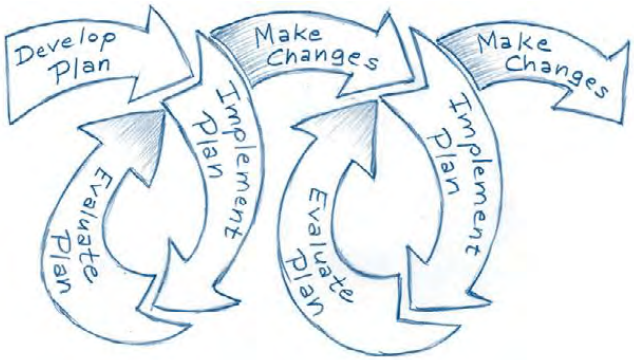
Treatment trains that include treating a tributary with alum, collecting deposited sediment, constructing and restoring wetlands in the near-lake areas, and harvesting wetland biomass to remove nutrient loading from the system were proposed for multiple locations in the plan for cleaning up Grand Lake St. Marys in Ohio (Tetra Tech 2010b). Three treatment train systems have been established and are operational on Prairie, Coldwater, and Beaver Creeks within the watershed. Prairie Creek has an engineered system that includes a Mobile Alum Injection Device as well as extensive constructed and restored wetlands (KCI Associates of Ohio 2017). Monitoring data indicate that removal efficiencies at Prairie Creek were 31 percent and 71 percent for nitrogen (NO_2-N, NO_3-N, NH_3-N) and phosphorus ($P0_4$), respectively. Coldwater Creek also has an engineered system, similar to, but larger than, the one at Prairie Creek. The system at Beaver Creek consists of a Biofilter Complex treating water in three vegetated cells. A system for Big Chickasaw Creek is being designed for implementation in 2018. Systems at Beaver Creek and Prairie Creek were funded by the Section 319 Program, whereas those at Coldwater Creek and Big-Little Chickasaw Creek are funded through state appropriations.

Treatment systems are also applied in the urban sector. For example, the Minnesota Pollution Control Agency (MPCA) stormwater manual (MPCA 2015) states that stormwater treatment trains have been loosely defined as multi-BMP approaches to managing the quantity and quality of stormwater runoff. Treatment trains have included prevention, source control, and treatment practices. MPCA develops treatment trains based on the processes employed by the BMP, with a well-developed stormwater treatment train combining hydraulic, physical, biological, and chemical components in a manner that ensures management of all pollutants that have been identified as affecting the receiving water. A stormwater treatment train incorporates at least two processes to maximize the control of pollutants from the runoff. The BMP(s) selected may consist of one or multiple practices, depending on many considerations, including available space, physical conditions at a site, and regulatory requirements.

According to the Mid-America Regional Council (MARC 2008), a treatment train combines site development strategies, management and housekeeping practices, and engineered solutions. Their elementary treatment train concept begins with open space (e.g., disconnect impervious surfaces with native vegetation), followed in order by source control BMPs (e.g., infiltration trenches), source filtration BMPS (e.g., bioretention), regional retention and treatment (e.g., constructed wetlands), and delivery to receiving waters by surface water, groundwater, or the sewer system.

Lesson: Adaptive Management is Essential to Achieving Treatment Goals

Adaptive management and the use of interim milestones are essential to address unforeseen shortcomings in the determination of CSAs, the implementation of planned practices, or the effectiveness of implemented practices. Regardless of the data or tools used when CSAs are determined and treatment plans are developed, the execution and effect of the effort will often differ from what was envisioned due to many factors, including the assumptions made in and the inherent uncertainties of such a planning exercise, as well as the dynamics of both the social and biophysical processes. As described by USEPA (2008), the activities involved in watershed assessment, planning, and management are iterative, and targeted actions might not result in complete success during the first or second cycle.



By tracking and evaluating progress, projects can make needed adjustments to increase the likelihood that water quality goals are achieved. For example, the ten-year evaluation plan for the Lower Big Rib Priority Watershed Project in Wisconsin consisted of an annual administrative review, pollution reduction evaluation, water resource monitoring, and a final report (Davenport 2002). Failure to achieve a 5-year interim target for sediment load reduction would have resulted in an increase in the number of agricultural fields included in the CSA.

1.2 Purpose

This document is intended to help watershed project teams define CSAs where appropriate BMPs will be implemented to achieve water quality goals in the most efficient manner possible. Effective determination of CSAs will usually result in identification of smaller areas within a watershed that contribute a disproportionate amount of pollutants of concern or contribute otherwise in a disproportionate manner to the identified water resource problems of concern. This will support targeted, cost-efficient implementation of practices and measures to meet water quality goals in a timely manner.

This document is not a technical how-to manual with step-by-step procedures or solutions for all watersheds, but is rather intended to inform such site-specific actions carried out at the local level. The background information, methodology, examples, and overview of data sources and tools are intended to document progress made in this area and provide a platform for enhancing the state of the art. While the document is based on a rigorous review of past and current efforts to define and treat CSAs, approaches and tools continue to evolve and practitioners will need to track new developments.

1.3 Critical Source Area Definition

Critical source areas are those areas within a watershed that contribute a disproportionately large amount of pollutants of concern to the identified water quality problems. They are generally considered to be places where high-level pollutant sources overlap or interact with high pollutant transport potential (Ghebremichael et al. 2012, Giri et al. 2016, Meals et al. 2012), as illustrated in Figure 3. As can be seen from Figure 3, combinations of lesser pollutant sources with greater transport potential or greater pollutant sources with lesser transport potential can also result in areas that are relatively more critical than others. The amount of pollutant reduction needed to achieve water quality goals will determine the extent to which these less critical sources are included in the treatment plan.

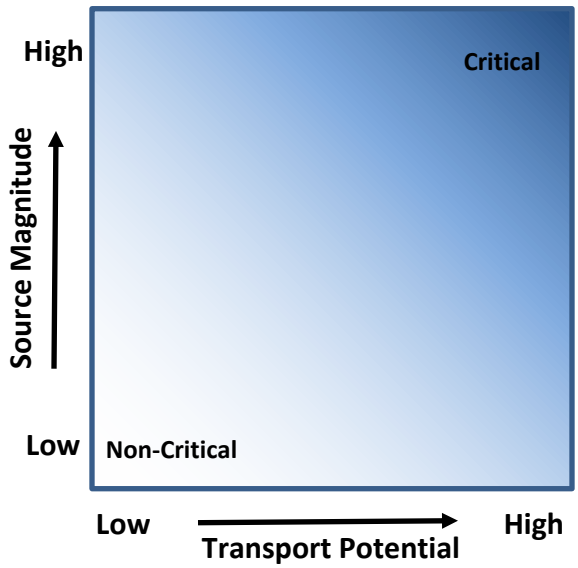


Figure 3. Conceptual relationship between pollutant source magnitude and transport potential.

2. Identifying Critical Source Areas and BMP Selection

Accurate identification of CSAs and selection/prioritization of BMPs and other management measures is required to ensure that overall treatment performance is sufficient to achieve pollution reduction targets. Identification of CSAs and BMP selection is largely a technical matter involving many variables and choices (Figure 4). The process includes establishing priority locations where water quality improvements are most needed, describing information on pollutant pathways/transport mechanisms relative to potential sources, estimating the relative source contribution based on existing land use/land management, and rating source areas in a way that considers the performance of BMPs and other measures as well as opportunities to implement additional or modify existing practices (Figure 5[1]).

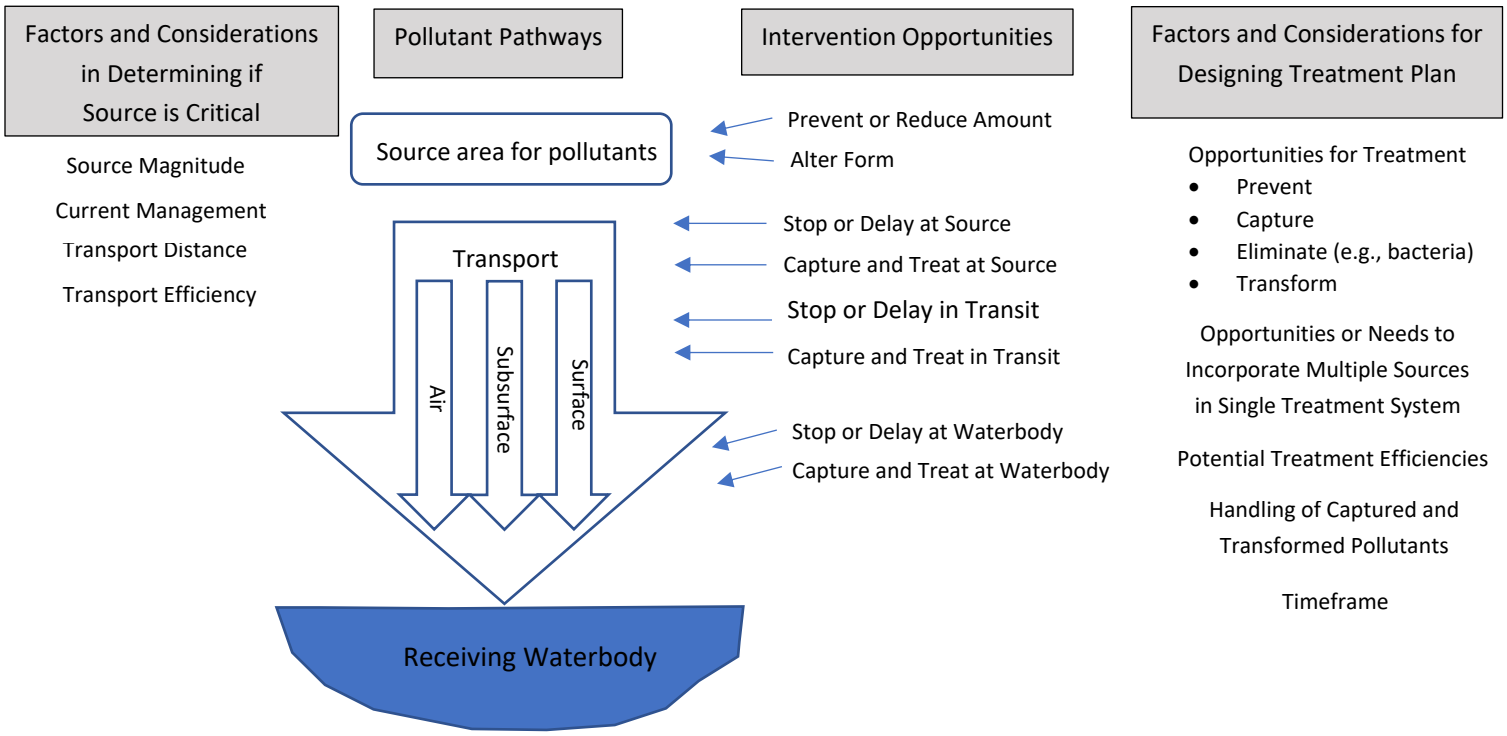


Figure 4. Factors and considerations for CSA delineation and BMP selection.

Success of the targeting approach, however, requires that the needed BMPs and other measures are implemented in a timely manner. It is therefore necessary to also give attention to the human element. Full consideration must be given to the availability of both voluntary and regulatory programs (i.e., management tools) to support practice implementation, and, in the case of voluntary programs, the willingness and ability of landowners and managers to implement needed BMPs and other measures. Both CSA identification and selection of BMP/management tools to achieve implementation fall within the broader scope of watershed management described by USEPA (2008). Consistent with that watershed approach, the CSA analytic approach presented here consists of two central components:

[1] Figure 5 icons are used in sections 2-4 to indicate the stage in the process to which the section applies.

1. A *data-driven assessment* of factors to identify *priority locations* where water quality improvements are most needed and there is a high probability of pollutant delivery to receiving waters.
2. *Management tools* to support or promote *BMP implementation* in those priority locations.

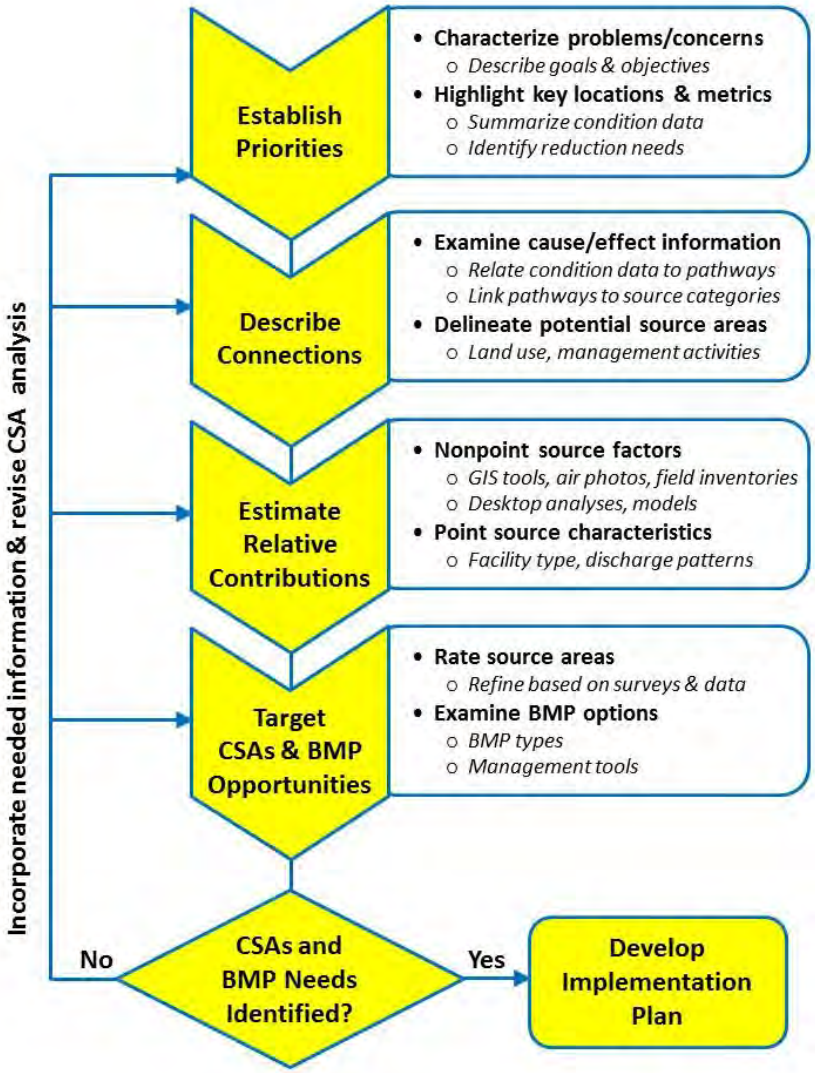


Figure 5. Process overview for identifying CSAs and BMP opportunities.

The following sections describe steps (Figure 6) that should be taken in any process to identify CSAs and select BMPs and other measures for implementation. These steps fall within the four basic phases outlined in Figure 5:

- Establish priorities
- Describe connections/linkages from transport pathways to potential sources
- Estimate relative source contributions
- Identify CSAs and BMP performance expectations and implementation opportunities

Monitoring progress toward achieving interim and overall water quality management goals and objectives provides essential feedback for making adjustments as needed. While listed in order, these steps may occur

simultaneously, in slightly different order, or iteratively, depending on specific issues, data availability, and process dynamics. Examples are included to illustrate specific approaches that have been used to address various steps in the process.

Establish Priorities

- Characterize the water quality issue, problem, or impairment that is to be addressed.
- Determine pollutant load or impact reduction targets that must be achieved to meet water quality goals.

Describe Connections

- Delineate the surface water, subsurface water, and atmospheric contributing areas.
- Identify and characterize all potential sources, progressing from a broad assessment of land-use/land-cover to a detailed characterization of potential specific sources, including sources within the transport system.
- Characterize pollutant transport pathways.
- Narrow the identification of potential sources to a set of potential critical sources.

Estimate Relative Contributions

- Determine current management of potential critical sources to assess the magnitude of pollutant or impact reduction that could be achieved with improved management or elimination of the sources.

Target CSAs and BMPs

- Refine CSA delineation and establish BMP performance requirements to achieve water quality goals.
- Assess alternative treatment scenarios and prioritize sources for treatment.

Monitor Progress

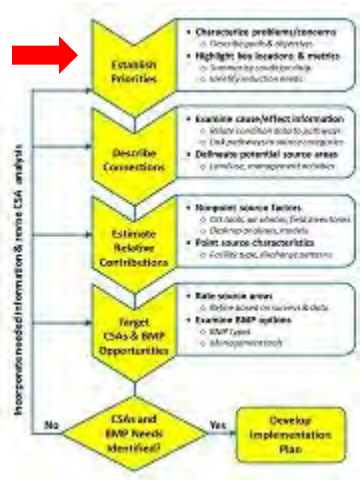
- Track CSA treatment and water quality versus baseline and target conditions to assess progress in achieving project objectives.
- Make necessary adjustments and continue monitoring progress.
- Repeat as necessary.

Figure 6. Steps for CSA delineation and BMP selection.

2.1 Establish Priorities

Watershed projects should be designed to achieve specific objectives that are based on the best available information and logical rationale, not available resources. Objectives may include:

- Restoring impaired waters
- Protecting high-quality waters
- Directing resources to locations where BMPs will be most effective



For this approach, we assume the following:

- The watershed project has clearly and accurately characterized the water quality problem or impairment that is to be addressed.
- The watershed project has already determined pollutant load or impact reduction targets that must be achieved to meet water quality goals.

2.1.1 Water Quality/Flow Analysis

As noted in Section 1.1, visual observation can be a valuable source of information about water quality and watershed conditions, particularly in cases where water quality monitoring and flow data are generally unavailable. Initial examination of the watershed can be carried out as a screening exercise or as a formal inventory, depending on project needs. Visual observation of excessive algal growth, scoured streambanks, sediment deposition, discharge pipes, and other unusual features can provide information about potential water quality or flow issues. In some watersheds it may be possible to perform stream walks or canoe the stream during both low-flow and higher-flow conditions to see where major inflows exist. Measurements of instantaneous flow, dissolved oxygen, conductivity, temperature, and turbidity at multiple points with a hand-held meter can provide some indication of pollutant influx at various points in a stream system, particularly if abrupt changes in measured values occur.

Where data exist for multiple monitoring stations in a watershed, a comparison of simple descriptive data summaries can yield information regarding potential sources. Methods for exploratory data analysis, including data management, one-dimensional analysis (e.g., basic statistics for a single parameter), and two-dimensional analysis (e.g., compare phosphorus levels at two stations), are described in detail by Dressing et al. (2016). Simple boxplots, for example, can be used to compare pollutant concentrations at two or more stations as an indication of relative pollutant contributions. The example in Figure 7 shows a substantial difference in TSS between Stations 1 and 3, as indicated by the lack of overlap between the two boxes. Increased concentrations of a pollutant between two stations could result from stormwater discharges, tile drain outlets, or subwatersheds contributing a disproportionate share of pollutants. Such circumstances could be confirmed with a stream walk. Decreased concentrations could indicate, for example, (a) a gaining section of stream where groundwater inputs are significant or (b) contributions from source areas with much lower unit-area pollutant loads. If both the contributing subwatershed area and upstream and downstream discharge rates are measured, the unit-area load of the contributing source can be estimated.

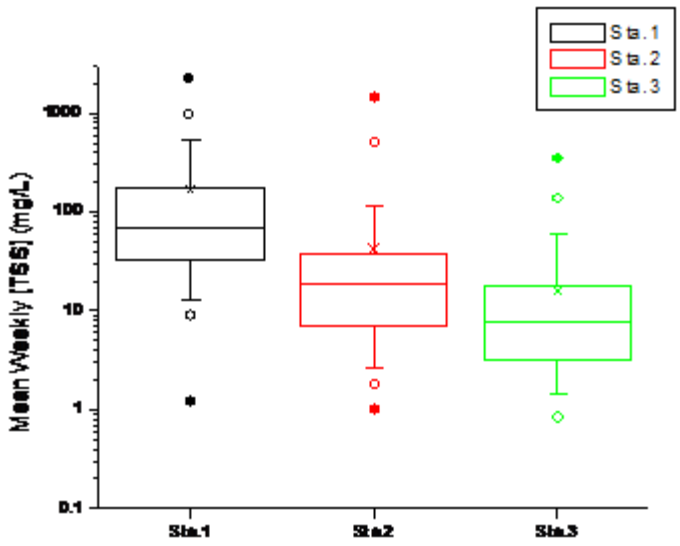


Figure 7. Boxplots of TSS concentration for three stream stations, 1998 (based on Meals 2001).

Differences in pollutant concentrations between baseflow and high-flow conditions can also provide indications of major source locations and the primary pollutant pathways. Base flow is typically fed by groundwater sources and continuous discharge sources (e.g., wastewater treatment plant (WWTP) discharge), whereas high flow is usually comprised mostly of surface runoff.

Where projects have a more extensive dataset and advanced analytical capabilities, seasonal differences in pollutant concentrations during both baseflow and high-flow conditions should also be examined. In agricultural settings, application of nutrients and tillage activities are generally seasonal in nature and are often related to observed changes in nutrient, bacteria, or sediment levels in streams. In urban settings, application of pesticides and fertilizers to lawns is also generally seasonal in nature, as are changes in WWTP discharges in tourist areas, or pollen or leaf deposition on streets. Figure 8 and Figure 9 illustrate how temporal patterns in contributions from pollutant sources can be assessed with a robust water quality data set (Tetra Tech 2016b). In this case, data illustrate the effect of tile drainage on phosphorus concentrations, particularly during spring runoff and following summer storms (red circles). These data provide an example of how knowledge of land use and land management are used to interpret observed patterns in water quality data.

More advanced tools such as microbial source tracking can be used to narrow options for sources of certain pollutants. Microbial source tracking procedures use host-specific (i.e., found only in one host species or group) or host-associated (i.e., largely confined to one host species or group) microbial indicators to establish the origin of fecal pollution in water (Meals et al. 2013).

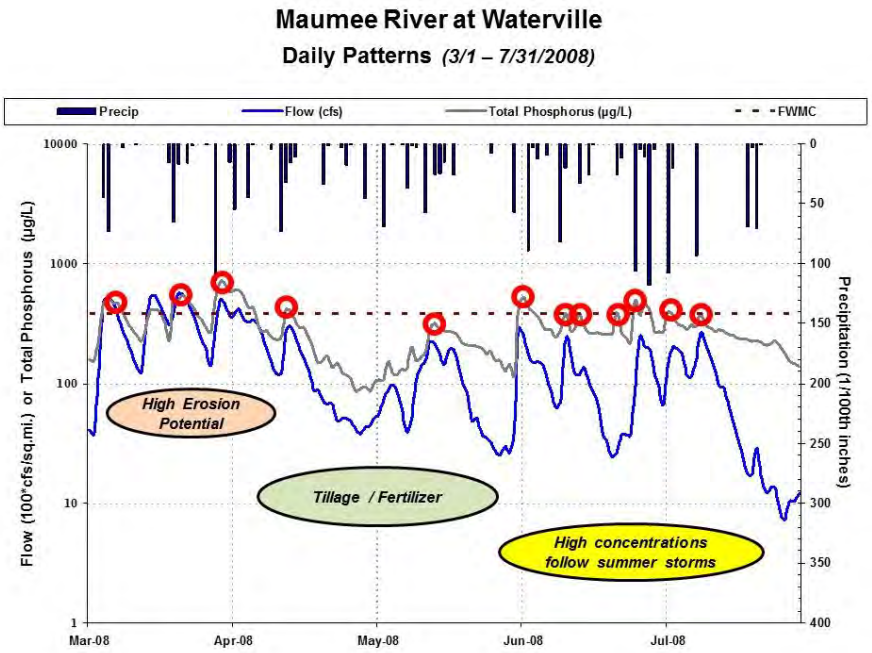


Figure 8. Maumee River total phosphorus daily patterns (March – July 2008).

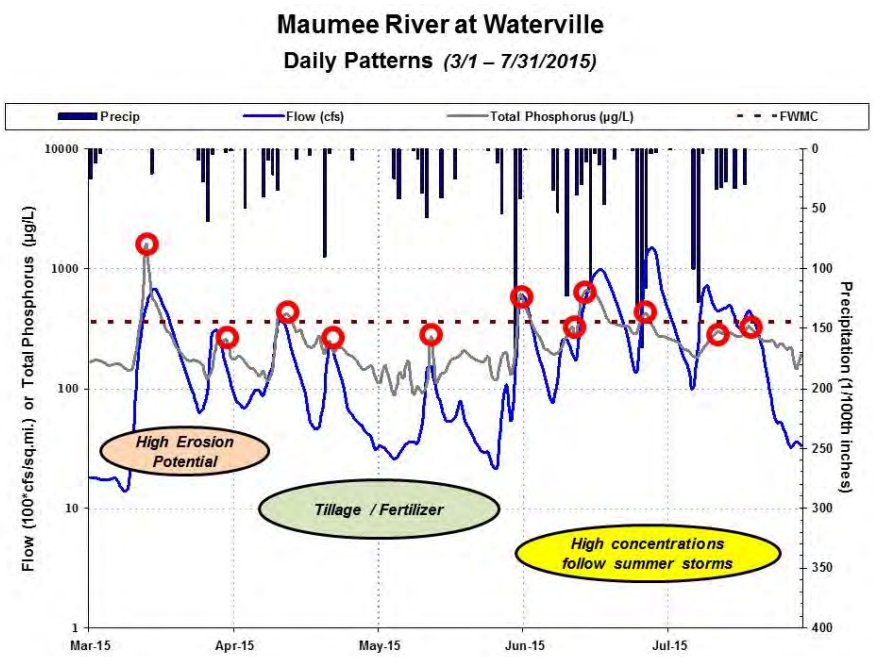


Figure 9. Maumee River total phosphorus daily patterns (March – July 2015).

2.1.2 BIOASSESSMENTS

Many states assess biological conditions to determine if aquatic life uses are impaired or water quality problems exist. Common approaches include methods that evaluate the condition of macroinvertebrate or fish communities; results are generally expressed through indices (e.g., Index of Biotic Integrity, Invertebrate Community Index). As with water chemistry data, biological assessments can provide valuable information to target priority locations of concern. For projects where such biological monitoring is not performed by state or other experts, there are numerous sources of guidance for citizen-based biological and water quality monitoring (USEPA 2017c). Guidance is also available to ensure that the data collected by citizens is of high quality and meets project requirements (USEPA 2017c).

Multiple lines of evidence are often used to determine potential causes and source areas, including CSAs where appropriate BMPs can be implemented to achieve improvements in water quality. For example, the *Stressor Identification Guidance Document* (USEPA 2000) describes a systematic process that can be used by projects with advanced biological monitoring expertise to connect biological assessment information to potential causes and sources.

A closer examination of the bioassessment data (e.g., key index component metrics) by expert biologists may shed light on priority locations for treatment to address aquatic life use impairments or concerns. This includes evaluating reasons for poor scores (e.g., lack of species diversity, high proportion of pollution tolerant organisms, dominant taxa characteristics). To address impairments or concerns with maximum effectiveness, management solutions must target the specific causes of biological impairment where they occur.

One example that illustrates the utility of bioassessment information in targeting treatment to potential CSAs is Ox Creek, a Midwestern stream where benthic macroinvertebrate data showed a lack of species diversity dominated by pollution-tolerant oligochaetes (Tetra Tech 2010a). As burrowers, these organisms can survive in aquatic environments with excessive sedimentation. In this case, biological monitoring data helped target the priority locations that need to be addressed. A closer look at species composition pointed to potential source areas, including sedimentation from surface and/or channel erosion.

Figure 10 illustrates a process for assessing the relationship between biological impairments and major watershed processes that contribute to problems such as degraded habitat. In this case, habitat is degraded by siltation that is linked to suspended solids delivered by high stormwater volumes. The actual linkage to stormwater may require an analysis of available water quality and flow data, but could also be performed in a qualitative manner through visual observation during storm events.

Relationships shown in Figure 10 have also been used in urban settings where increased “flashy flows” associated with excess stormwater volume have resulted in poor macroinvertebrate scores. Figure 11 provides such an example where data collected by local watershed groups highlighted key locations where scores were fair to poor. The subsequent analysis ultimately identified connected impervious surfaces associated with high volume transportation corridors as CSAs.

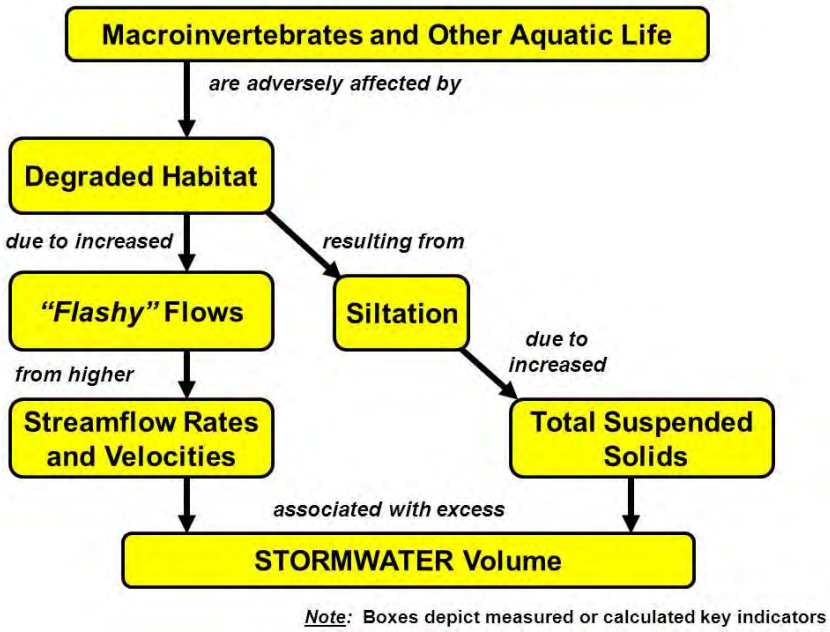


Figure 10. Relationship between biological concerns and key indicators connected to potential CSAs.

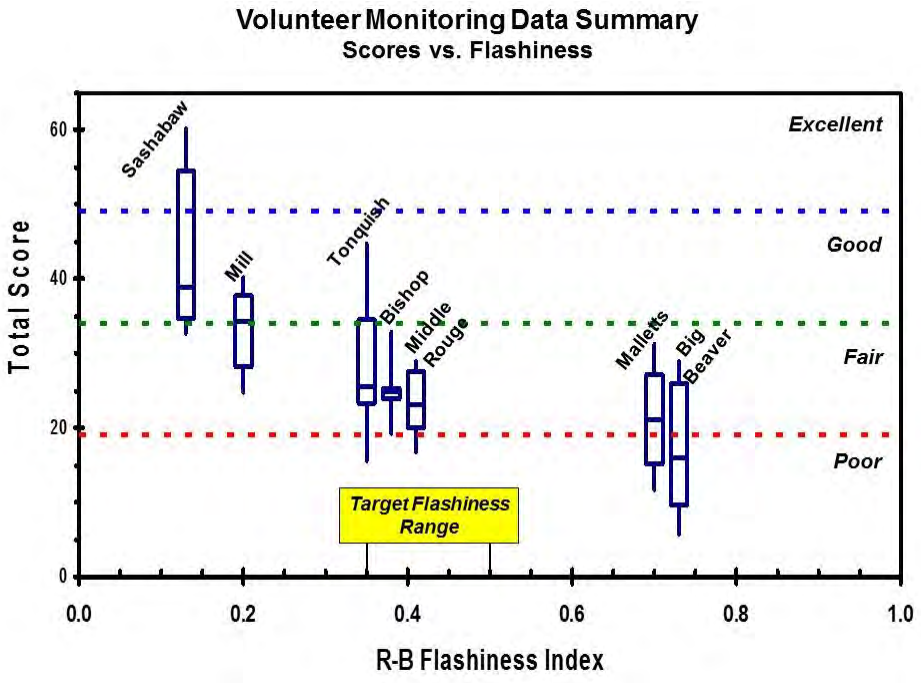


Figure 11. Comparison of stream flashiness to bioassessment scores.

2.1.3 Habitat Evaluations

Stream habitat information can also help establish priorities for addressing identified watershed problems. Selected habitat characteristics commonly measured in NPS monitoring programs are listed in Table 2 (Dressing et al. 2016). A number of states have developed protocols for conducting qualitative habitat evaluations. Ohio, for example, uses the Qualitative Habitat Evaluation Index (QHEI) (Ohio EPA 2006). Values for the QHEI index are based on measurements of:

- Substrate: type and quality
- Instream cover: type and amount
- Channel morphology: sinuosity, development, channelization, stability
- Riparian zone: width, quality, bank erosion
- Pool quality: maximum depth, current, morphology
- Riffle quality: depth, substrate stability, substrate embeddedness
- Map gradient

Jessup and Dressing (2015) describe the following methods for measuring bedded sediments and bank stability:

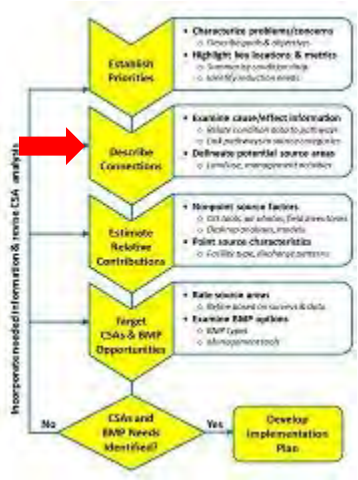
- Embeddedness and sedimentation ratings
- Surface particle size distribution
- Relative Bed Stability
- Bank stability ratings
- Sequential channel surveys
- Bank Erosion Hazard Index
- Near-Bank Stress

Habitat characteristics include attributes that may contribute to water quality problems and connect to potential source areas. These attributes are typically grouped either by in-channel metrics (e.g., siltation, embeddedness, width:depth ratio, bank erosion, pool quality) or by riparian condition. Adversely affected in-channel metrics could be indicative of potential upstream sources. For example, excessive siltation or substrate embeddedness could result from source areas associated with surface erosion (e.g., poor management practices on agricultural fields, construction sites, or areas on actively managed timber lands). Other examples include high channel width:depth ratios or active bank erosion resulting from flashy stream flows caused by urban runoff from impervious surfaces or coarse sediment deposition from forest practices (e.g., logging on steep slide prone slopes, poor road construction). Similarly, adversely affected riparian metrics could indicate the presence of more localized CSAs such as livestock access to streams or lack of adequate riparian buffers.

Table 2. Selected habitat variables commonly measured in NPS watershed monitoring programs

Variable	Definition	Notes
Bottom substrate	Percent rubble or gravel, presence of undercut banks, woody debris	Quality and diversity of substrate influences suitability for fish reproduction and habitat quality for benthic invertebrates.
Embeddedness	Percent gravel, cobble, and boulder particles surrounded by fine sediment	Substrate condition influences suitability for fish reproduction and habitat quality for benthic invertebrates.
Flow velocity	Range of current velocity	Prevailing current velocity influences suitability for stream biota.
Channel alteration	Channelization, presence of point bars, silt deposition	Altered channels may reduce habitat diversity; sediment deposition can render substrate unsuitable for fish or invertebrate communities.
Pool/riffle ratio	Variety of pool/riffle environments	A diversity or, alternatively, a lack of pool and riffle environments influences suitability of a stream environment for fish and other biota.
Qualitative Habitat Evaluation Index (QHEI)	Multiple metric index of habitat variables including substrate, cover, channel quality, riparian condition, bank erosion, pool/riffle distribution, drainage area, and gradient	The QHEI is composed of an array of metrics that describe attributes of physical habitat that may be important in explaining the presence, absence, and composition of fish communities in a stream. A significant correlation between QHEI and IBI (Index of Biotic Integrity) has been documented in Ohio.

2.2 Describe Connections



As discussed above, CSAs are often defined as an overlap of high pollution source areas with hydrologically sensitive areas or areas prone to generating high volumes of runoff, erosion, or pollutants of concern. If the water resource to be protected is groundwater, however, hydrologically sensitive areas may be those areas prone to generating high volumes of infiltration or recharge to the groundwater system. Similarly, some pollutants may be derived from airborne sources that should be considered when defining CSAs. An initial broad view of potential sources and pollutant pathways is essential to developing an approach that will lead to successful CSA delineation. As shown in Figure 12, pathways and sources of pollutants or impacts can be identified by working both forward and backward from the water resource of concern to potential sources. Assessment of pathways with the greatest transport potential and areas with the greatest sources of targeted pollutants or impacts provides the information necessary to identify overlaps where CSAs are likely to exist. Inherent in this analysis is an assessment of current management and the opportunity to effect improvements to achieve pollutant or impact reduction targets.

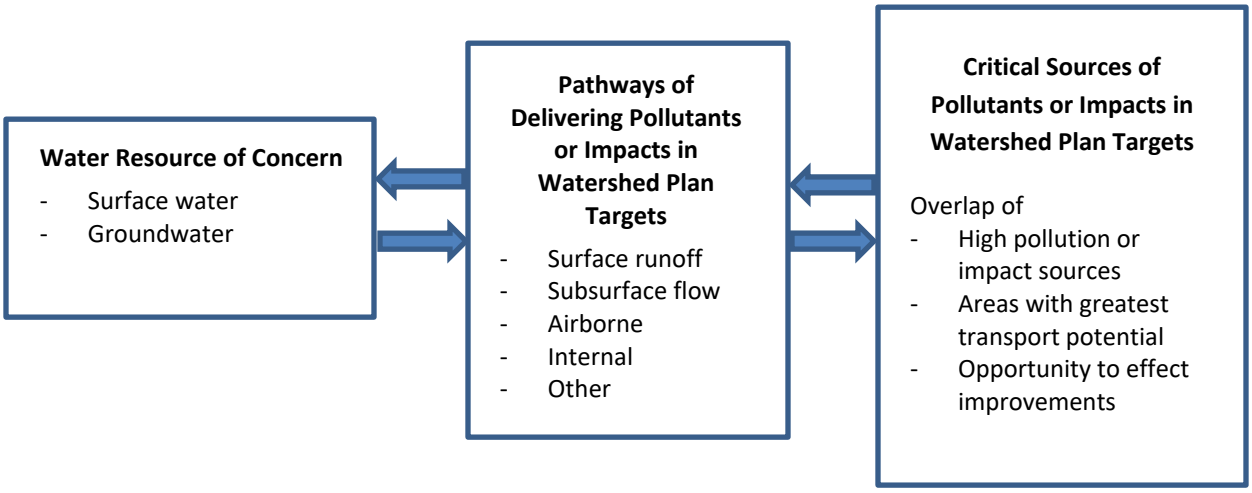


Figure 12. Overview of process to identify critical transport and pollutant or impact sources.

2.2.1 Pollutant Pathways

As described by Blanchard and Lerch (2000), the chemistry of a compound determines the potential hydrologic transport pathways, and watershed hydrology determines the relative importance of the leaching and runoff transport pathways in agricultural watersheds. Land use, including the percentage of a watershed that is cropped, the locations within the watershed that are cropped, and the chemicals applied, constitutes the third important factor. Hydrology is largely determined by the soils, as reflected by soil hydrologic groups. The authors conclude that water quality practices must be designed in accordance with the dominant problems and transport pathways of a watershed. Linard et al. (2009), however, point out that the processes controlling the fate and transport of agricultural chemicals are generally understood only conceptually at the watershed scale. In urban settings pollutant transport is often governed more by the extent of connected impervious surfaces (CASQA 2003b).

Various methods have been developed to simulate watershed hydrology, including the curve number method (USDA-NRCS 1986), the Green and Ampt method (Craig et al. 2009), and the TOPMODEL algorithm (Linard et al. 2009). Models such as SWAT and the Water, Energy, and Biogeochemical Model (WEBMOD) incorporate these methods (Webb and Parkhurst 2017). Devi et al. (2015) reviewed the variable infiltration capacity model (VIC), TOPMODEL, HBV, MIKESHE and SWAT. An inventory of hydrological models is maintained at Texas A&M University (TAMU/BOR n.d.).

Hydrological modeling can aid in the identification of CSAs, but many watershed projects lack the resources and data to support such modeling. Where hydrological modeling cannot be performed, likely pollutant transport pathways can be identified by examining the following: maps of the stream network, stormwater management system, or agricultural drainage network; information on soil types (hydrologic soil group); land cover data; location of impervious surfaces; and topography. Figure 13 illustrates an overlay approach to identifying potential CSAs. Layer A shows the stream network, B shows areas where cut streambanks and heavy sedimentation were identified by a volunteer monitoring group, C shows the road network, and D shows activities and sources of interest that were identified during a windshield survey. In this simplified example, pollutant pathways were addressed qualitatively based on the relationships between identified problems (sediment in this case) and potential sources. It was assumed that the large parking lot could contribute erosive flows during storm events, thereby contributing to the streambanks cuts. New construction along the stream was assumed to contribute to the heavy sedimentation downstream. In addition, sediment from the highly erosive upstream cropland areas could likely be delivered downstream to the problem area. It was also assumed that the two stream crossings could contribute erosive flows through scupper drains or roadside drainage.

After assembling background maps and other information described above, project participants should walk the watershed to examine pollutant pathways. In the case of the map overlays (Figure 13), visual inspection during a rainfall event would be essential to confirming assumptions made in identifying the potential CSAs (see Section 2.3.1 for additional information on visual observation). Because sediment is the pollutant of interest in this example, visual inspection can yield useful information regarding pollutant pathways. For example, evidence of sediment deposition downstream from the highly eroding cropland might confirm the importance of that source, but the entire pathway to the receiving stream with heavy sedimentation problems would need to be examined.

In cases where modeling is performed, visual inspection of the watershed, particularly during runoff events, is strongly recommended to verify modeling results. It is important to keep in mind that modeling will only provide an approximation of pollutant pathways. Specific sites that are averaged or overlooked in the modeling process may be found to contribute far more significantly than indicated by modeling results. In turn, other sources deemed critical through modeling may be found to be less significant pollutant contributors due to site-specific conditions or management.

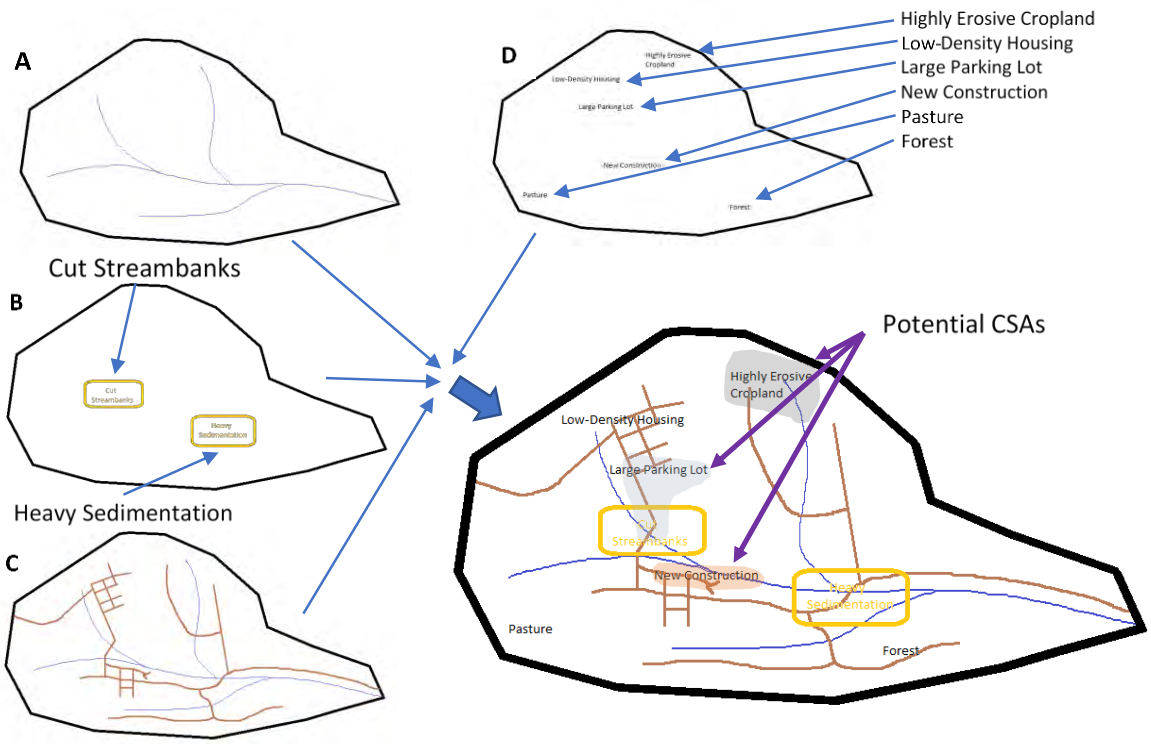


Figure 13. Illustration of simple map overlays.

Greater resolution can be obtained by examining available data on stream flow, stormwater discharge, and existing BMPs or other treatment. Another factor to consider is whether impervious areas outlet directly to the drainage system (connected) or whether the flow spreads over pervious areas before entering the drainage system (unconnected). Implemented BMPs and connectivity can be assessed as part of the visual inspection if site access is available.

Lag time must be considered to the extent possible with available data and tools (Meals et al. 2010). The International Missisquoi Bay Study Board (IMBSB 2012) acknowledged the importance of lag time, noting studies that indicated different short-term benefits from CSA management at different geographic scales. At field and small watershed scales (25 to 741 acres), management yielded significant reduction of N and P loss over the short term (1 to 10 years). At smaller geographic scales, however, they found that several studies showed no short-term benefits from CSA management due to factors such as in-stream processes, vertical stratification of P in no-till fields (increased soluble P loss), and legacy landscape sources of P (enriched soils).

Lag time in urban settings is very different from that in agricultural watersheds. As illustrated in Figure 14, impervious cover directly influences urban streams by dramatically increasing surface runoff during storm events (FISRWG, 1998). Depending on the degree of watershed impervious cover, the annual volume of storm water runoff can increase by 2 to 16 times its predevelopment rate, with proportional reductions in groundwater recharge (Schueler 1995). The increase in runoff relative to infiltration, coupled with the prevalence of rapid runoff conveyance systems in urbanized areas, will generally result in far shorter lag times than in rural settings.

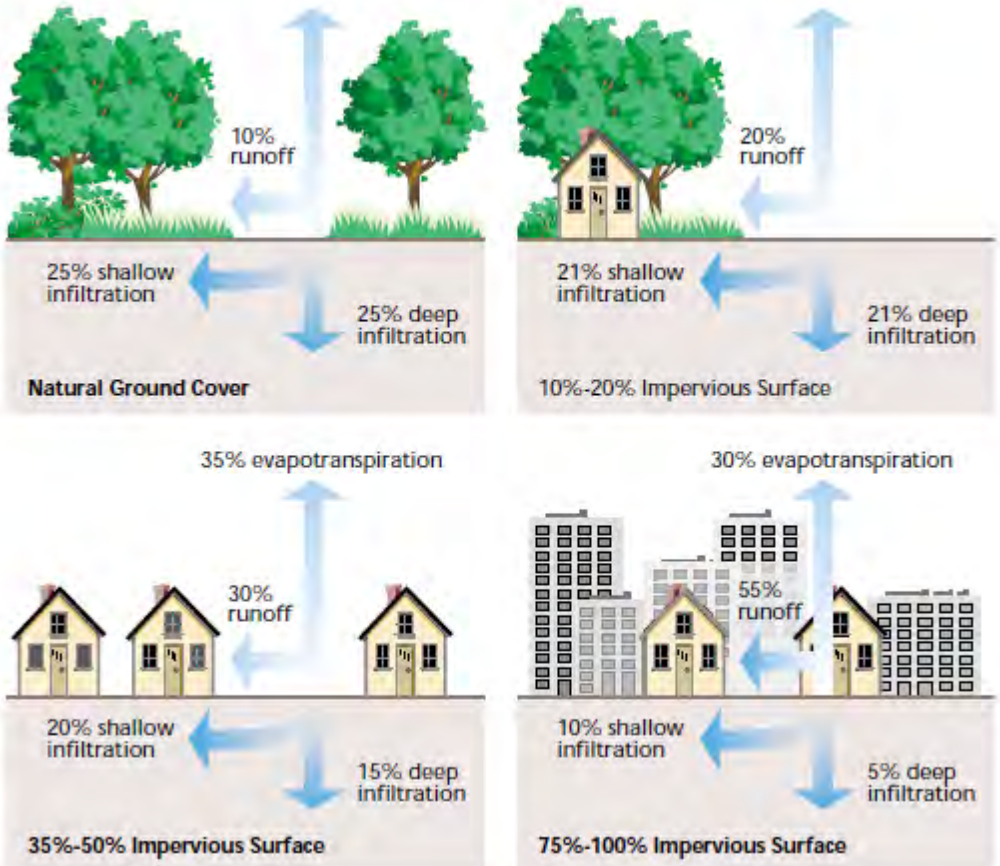


Figure 14. Relationship between impervious cover and surface runoff.

2.2.2 Critical Sources of Pollutants or Impacts

Identification of critical sources of pollutants or impacts should be conducted comprehensively to ensure the most efficient targeting of treatment. Whereas pollutant pathway assessment (Section 2.2.1) or anecdotal information may lead to the conclusion that certain sources are more problematic than others, a more careful follow-up assessment of all potential sources may yield a different conclusion. As an example, investigators addressing eutrophication problems in the Cannonsville Reservoir in New York under the Model Implementation Program initially believed that dairy barnyards were the largest sources of phosphorus pollution. Only after comprehensive monitoring data were collected and analyzed did they realize that the largest source of phosphorus was runoff from fields receiving manure (Brown et al. 1989). Most projects will not have monitoring efforts equivalent to that used in this case, but proper application of other tools and approaches described in this section could yield similar conclusions.

All available information, including anecdotal evidence, should be used when determining the locations of critical sources. All sources should initially be considered as potential critical sources when performing this assessment, despite preliminary conclusions that may be made during the assessment of pollutant pathways. For example, approaches using map overlays without models may be particularly prone to errors associated with soluble pollutants (e.g., nitrate nitrogen) because such pollutants (unlike sediment) cannot be seen during visual observations. Therefore, field confirmation of conclusions drawn from the map-based analysis is difficult.

Prioritization of detailed analysis based on the assessment of pollutant pathways may be warranted, but few, if any, sources should be excluded from CSA consideration based solely on a pathway analysis because of the inherent uncertainty.

In agricultural settings, sources can be further characterized by obtaining information on the locations, sizes, and management of animal operations; the location and timing of applications of manure and other organic nutrient sources; phosphorus index values; artificial drainage networks; major crops and yields; soil types and slopes (topography); pesticide use; cover crop usage; and tillage practices. Sources for much of this information are described in Section 5. Because of privacy considerations, however, much of the USDA data on individual farm operations is not available. Project managers should develop an analytic plan and data needs to facilitate any request for information that is not easily obtainable. If, for example, the primary concern is pathogens, a focus on animal operations and the handling, transport, and application of animal manure would be appropriate. Both farm operations with animals and those receiving manure from others should be included in the analysis. Potential contributions from wildlife should also be assessed.

In urban settings, knowledge of the stormwater collection network, existing stormwater management practices, land use and land cover (zoning maps), point source discharges, the road network, topography, and soils are all important to an initial assessment of potential critical sources. Source assessment should also consider in-lake or in-stream sources (e.g., internal recycling). As for agricultural sources, visual inspection will help confirm the validity of information collected from databases. A potential advantage in urban settings is greater access to potential sources of interest as many will be public lands or areas with unlimited access (e.g., parking lots). It is also possible to focus efforts in the urban setting based on the pollutants of concern. If, for example, salinity is a concern in a northern climate, project managers may decide to focus on storage and handling areas for road salt, or simply the roads themselves.

2.2.3 Determination of Potential Source Areas at Watershed Scale

The delineation of CSAs should be considered a multi-tier process in which broad-scale assessments are followed by smaller-scale assessments to nail down specific details and refine estimates of potential load reductions within the CSA. Analysis at the subwatershed scale (up to about 40,000 acres) is the logical first step in this process. Pollutant pathways and potential critical sources are identified at this scale to provide a first-cut estimate of the CSA and priority concerns.

A drainage assessment is conducted within the watershed by combining information on watershed conditions and stream and stormwater management networks. The drainage assessment highlights CSAs where BMP implementation will be most effective (i.e., areas that have a disproportionate effect on hydrology and water quality). As described earlier, CSAs can generally be identified as the intersection of high-level pollutant sources and high pollutant transport potential. In an urban setting, for example, areas generating large amounts of sediment that are hydrologically linked to areas with impervious cover and conveyance systems may be CSAs for sediment. Other CSAs may be located in headwater areas and near local streams (e.g., road crossings, major stormwater outfalls).

The Center for Watershed Protection (CWP 2012) describes a process for identifying stormwater hotspots, defined as commercial, industrial, institutional, municipal, or transport-related operations that produce higher levels of stormwater pollutants or present a higher potential risk for spills, leaks, or illicit discharges. The California Stormwater Quality Association (CASQA) developed a series of BMP handbooks that provide information and guidance on identifying pollutant source areas and BMP opportunities for construction, industrial and commercial, municipal, and new development and redevelopment sources (CASQA, n.d.). For example, CASQA (2003a) provides

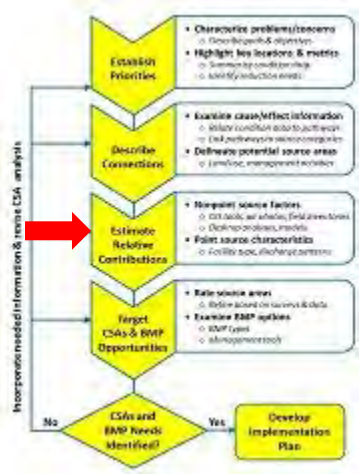
a list of typical municipal operations and pollutants they generate, including fixed facilities activities (e.g., building maintenance and repair, waste handling and disposal, and vehicle fueling and storage tank filling) and field program activities (e.g., street repair and maintenance, sidewalk surface cleaning, and solid waste collection and recycling).

Source area analysis may be conducted via modeling or other less expensive methods, including assessment of land use and impervious cover information in urban watersheds. Impervious surface composition (type, amount, density) is often characterized by land use category (residential, roads, etc.) to identify high priority catchments where: a) the total amount of impervious area is greater and b) the percentage of impervious cover is higher. The data may also be categorized by jurisdiction to describe the overall contribution by land use type and ownership. Coupled with rainfall data, impervious cover provides an estimate of potential stormwater runoff volume generated from various potential source areas.

As illustrated in Section 2.2.1, map overlays can be helpful in identifying major pollutant transport opportunities. Specifically, overlays of the stream network, the stormwater system in urban areas, agricultural drains and ditches, soils (hydrologic soil group), land cover type, impervious surfaces, and topography should provide some indication of the sources of specific pollutants. Tools for organizing and analyzing data include GIS which can be used to create maps and display and overlay spatial information for visual or modeling assessments. Figure 14 in Section 2.2.1 illustrates the application of GIS to layer data. Additional details on specific data sources and tools for this analysis can be found in Sections 5 and 6.

2.3 Estimate Relative Contributions

After initial assessment of potential source areas is completed at the subwatershed-scale, more detailed, site-specific information should be gathered to refine CSA delineation and estimate the relative pollutant contributions of sources within the CSA. This process can be carried out in many ways, but the essential elements are:



- Close inspection of potential source areas identified at the subwatershed scale, including confirmation of assumptions made (e.g., management level, pollutant pathways).
- Reconsideration of sources that may have been overlooked or underestimated in the subwatershed analysis (e.g., a streamwalk may change perspectives on contributions from stream banks or bottoms).
- Quantitative (preferred) or qualitative assessment of source areas to estimate relative pollutant contributions.

A wide variety of information and tools can be used to complete this phase of CSA delineation, including:

- Visual observations that incorporate local knowledge (e.g., field inventories, windshield surveys)
- Indices
- Available ambient monitoring data that reflects actual conditions in priority subwatersheds or catchments of interest
- Desktop screening tools and models

2.3.1 Visual Observation

The simplest way to improve the assessment of potential sources is to perform a visual inspection of sources and pollutant pathways. It may not be feasible to inspect all sources in larger watersheds or where access to sources is limited, but this basic tool can yield much information that is often unavailable through sources such as published datasets, agency records, or remote sensing methods. Visual observation can be performed at various scales (e.g., neighborhood, property, individual BMP) depending on need or priority, site accessibility, and resources.

While impervious cover composition provides a starting point to identify priority source locations in urban watersheds, for example, field inventory information is needed to refine the CSA analysis. The field inventory provides a focus on directly connected pathways, delivery mechanisms, and in-stream effects (particularly evidence of channel incision and bank erosion). This enables targeting specific critical locations where BMP implementation will be most effective in achieving overall watershed management objectives. The type of inventory information needed may include storm sewer system inlet points, outfall locations, riparian indicators, channel metrics, existing treatment, planned improvements, and stream conditions at road crossings. In agricultural watersheds, there may be a need for more refined information on animal populations, animal waste management practices, crop rotations, the presence and condition of field borders and riparian buffers, the location of drain tile systems and outlets, and the type and level of soil conservation and nutrient management practices.

Recommendations by Schueler et al. (1991) to walk the stream to gather information before proposing a BMP system in urban settings can also be applied to determining if a site is potentially a critical source. The following factors should be taken note of when performing this task:

- Watershed development (watershed area and watershed imperviousness)
- Urban BMP (proportion of contributing watershed controlled by a proposed BMP)
- Hydrologic change (dry-weather flow rate, watershed runoff coefficient)
- Channel form stability (form, dry-weather wetted perimeter, widening or downcutting, etc.)
- Substrate quality (bed sediment diameter, embeddedness, sandbars, discolored cobbles)
- Water quality (water temperature, slime, silt and sand deposits, benthic algae)
- Stream community (aquatic macroinvertebrates present on rocks, fish present)
- Riparian cover (presence/absence of and extent of riparian cover)
- Stream reach (presence/absence of pool/riffle structures, sinuosity, fish barriers, channel enlargement)
- Contiguous wetland (presence/absence and quality of non-tidal wetlands in riparian zone or floodplain)
- Floodplain change (constrained or unconstrained floodplain)

The CASQA BMP handbooks provide guidance on how to perform an inventory and assessment of sources (CASQA, n.d.). In addition, the information in these handbooks on best practices for protecting water quality can be used to help guide site assessments. For example, planning and design for protecting water quality from new development and redevelopment employs three basic strategies in the following order of relative effectiveness: 1) reduce or eliminate post-project runoff (e.g., by reducing impervious surfaces or connectivity), 2) control pollutant sources (e.g., by separating stormwater runoff from vehicle maintenance areas), and 3) treat contaminated stormwater runoff (e.g., through infiltration or retention/detention) before discharging it to natural waterbodies (CASQA 2003b). Shortcomings in these three areas should be identified and noted during site inspections to help identify CSAs.

Individual agricultural BMPs or BMP systems can be inspected if site access is granted. The USDA-NRCS Field Office Technical Guide (FOTG) provides standards and specifications for all conservation practices for each state (USDA-NRCS, n.d.). In cases where less rigorous assessments are needed, approaches such as those contained in the Chesapeake Bay Program (2014a) visual indicators guidance may be appropriate. These visual indicators are designed to provide for rapid and accurate assessment of a range of agricultural practices that can be assessed visually, including compost structures, grass buffers, and water control structures. Practices such as nutrient management cannot be assessed through these techniques.

Windshield surveys can be used to identify a range of features and practices of interest. Residue windshield surveys have been conducted for a few decades using a statistically-based approach (Hill 1998). Surveys can also be used to simply confirm information obtained from other sources (e.g., locations of bridges, tile drain outlets) or to obtain additional information about known features or locations.

As an example, the windshield survey conducted by the Defiance County SWCD (Figure 15) combined with a desktop screening assessment identified priority implementation opportunities in the upper Maumee watershed. The results of this evaluation show several potential CSAs (Table 3). Windshield surveys or field inventories that incorporate local knowledge provide a starting point for the CSA analysis in the Maumee. It is important, however, that these tools be applied properly (e.g., residue survey route developed in accordance with the procedure specified by Hill (1998)) to ensure reliable results.

The next steps after developing an inventory such as that shown in Table 3 would be to perform closer inspections of priority sources (e.g., Priority 1 streambank erosion at Zuber Cutoff, Gordon Creek, and Platter Creek) to confirm survey findings, develop estimates of relative pollutant contributions, and assess treatment opportunities. Available water quality data, unit area loading values from the literature, and models or spreadsheet tools can be used to estimate pollutant contributions (see Sections 5 and 6).

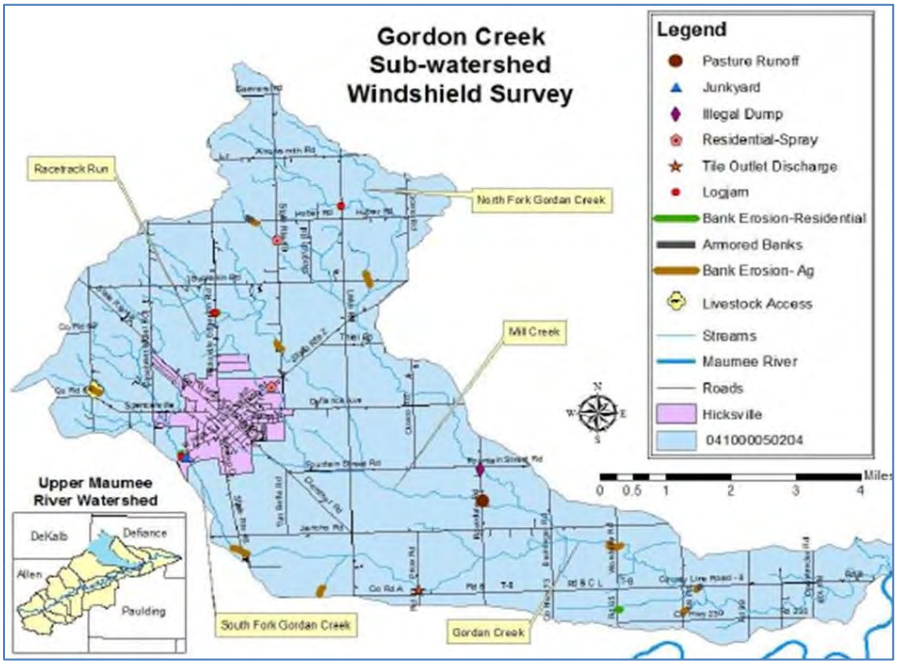


Figure 15. Example Defiance County SWCD subwatershed windshield survey map.

Table 3. Example subwatershed critical source area prioritization based on windshield surveys

HUC-12 *(041000)*		**Name**	**Critical source area Prioritization**				
			Streambank Erosion	*Urban*	*Livestock*	*Septic Failures*	*Sediment / Phosphorus*
05-02	01	Zuber Cutoff	●●●	○	◗	○	◗
	02	North Chaney Ditch-Maumee	n.a.	◗	◗	○	◗
	03	Marie DeLarme Creek	◗	○	◗	●●●	◗
	04	Gordon Creek	●●●	●●●	◗	○	◗
	05	Sixmile Cutoff-Maumee River	n.a.	◗	◗	◗	◗
	06	Platter Creek	●●●	○	●●●	○	●●●
	07	Sulphur Creek-Maumee River	○	◗	◗	○	●●●
	08	Snooks Run-Maumee River	○	◗	◗	○	●●●
06-06	04	Buckskin Creek-Tiffin River	n.a.	●●●	○	○	◗
07-12	09	Eagle Creek-Auglaize River	n.a.	●●●	○	○	◗
Notes: ●●● Priority 1 ◗ Priority 2 ○ Priority 3 n.a. Not prioritized							

2.3.2 INDICES

Indices that capture the magnitude and delivery potential of source pollutants can be used to help assess the relative contributions of sources. For example, the P index, an index ranking the relative risks of agricultural fields to phosphorus loss, has been used widely to help prioritize fields for nutrient and soil management practices (Ghebremichael et al. 2012, Osmond et al. 2012b). Sharpley et al. (2006) state that the P index accounts for the various transport and source factors controlling P loss in surface runoff. Other indices, such as the soil topographic index (Giri et al. 2016) and the travel-time phosphorus index (TTPI) (Buchanan et al. 2013), have been used to identify critical sources of pollutants. In some cases, index values have been overlain with maps of hydrologically sensitive areas to identify CSAs.

Heathwaite et al. (2000) demonstrated how indices for N and P can be used in tandem to identify CSAs specific to each pollutant (Figure 16). They first developed maps of transport factors for surface runoff (for P) and leaching potential (for N) for each pollutant. Surface runoff potential was generally greater nearer to the stream. Nitrogen transport was closely related to soil permeability. The near-stream areas in the study watershed had low vulnerability to nitrate loss because of their higher clay content and low permeability. The transport factors for P and N were multiplied by source factors which were based on land use and management to reflect potential loss of P and N, respectively. CSAs are those areas in Figure 16 that have “very high” vulnerability ratings. Treatment options would need to be tailored for each pollutant.

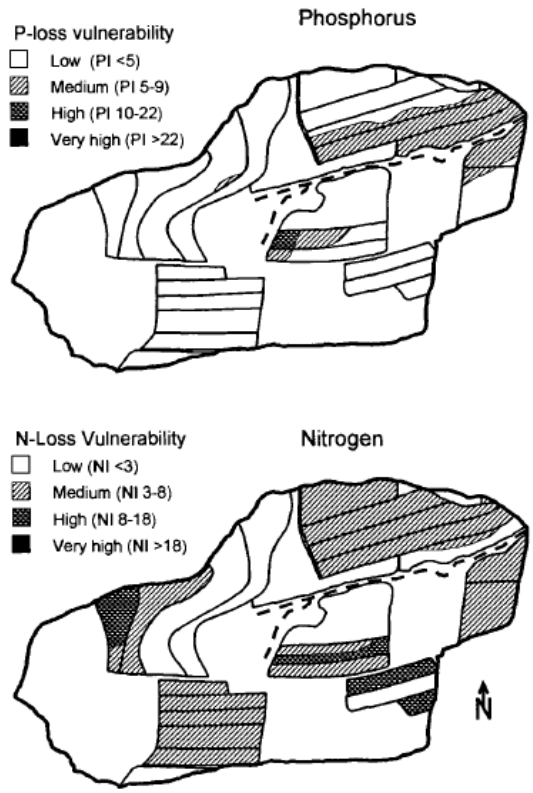


Figure 16. Application of phosphorus and nitrogen loss vulnerability indices (Heathwaite et al. 2000).

2.3.3 Water Quality Data

As described in Section 2.1.1, pollutant load estimates can be generated for specific sources or subwatershed areas if both flow and concentration data are available. Many samples are typically needed to accurately and reliably capture the true load pattern. Quarterly observations are generally inadequate, monthly observations will probably not yield reliable load estimates, and even weekly observations may not be satisfactory, especially if very accurate load estimates are required to achieve project objectives. Do not estimate annual loads based on simple multiplication of an annual average concentration and average discharge, as load estimates will be biased low for parameters such as suspended sediment and total phosphorus.

Richards (1998) describes several approaches to load estimation, including:

- Numeric integration
- Regression relationships between flow and concentration
- Ratio estimators

It is recommended that numeric integration be used when the full time-series of water quality and flow data are available as in the case of flow-proportional composited samples. Regression approaches are appropriate for incomplete water quality records if good correlations between water quality and flow exist, with the Beale ratio recommended otherwise. It is important to consider stratification by flow regime, season, and other covariates for both regression and the Beale ratio. See Section 7.9 of Dressing et al. (2016) for additional details regarding pollutant load estimation.

2.3.4 Desktop Analyses and Models

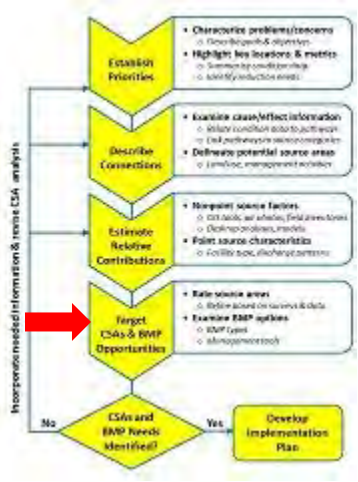
Desktop screening complements visual observations to identify significant catchments and locations within priority subwatersheds where an elevated risk of pollutant delivery may exist. Spreadsheets or simple decision tables can guide the analysis. Key factors often considered in this process include proximity to stream and runoff potential. Other factors deemed important are also typically incorporated into the process (e.g., soil phosphorus test values, field condition, connected impervious cover), along with follow-up though visual observations, field inventories, or use of aerial photos.

In urban areas, desktop analyses based on spreadsheets using effective impervious cover, rainfall, and a curve number approach can provide relative contribution estimates by examining runoff volumes across a range of reasonable assumptions for potential source areas. Similarly, literature values or empirical relationships based on local information can be coupled with rainfall, flow, and/or land use data to develop desktop screening analyses that provide relative estimates of pollutant load contributions. Duration curves illustrate yet another type of desktop screening analysis using spreadsheets to examine relative contributions based on hydrologic conditions (see Section 7.9.3 of Dressing et al. 2016). A key feature of load duration curve analysis is that the pattern of loads – and impairments – can be easily visualized over the full range of flow conditions. The pattern of observed loads exceeding target loads can be examined to see if impairments occur only at high flows, only during low flows, or across the entire range of flow conditions.

Watershed models such as SWAT, though generally more complex and resource intensive, can be useful in identifying CSAs. Because they incorporate hydrological simulations, these tools provide a more sophisticated approach to locating major pollutant sources regardless of location within the watershed. Complex models allow for quantitative consideration of possible pollutant losses, transformations, and gains (e.g., sediment resuspension in streams) throughout the various delivery pathways. Absent a robust set of water quality data or the ability to simulate pollutant pathways, other methods to locate critical sources often rely almost entirely on source magnitude and proximity to the delivery system (e.g., streams, ditches).

USEPA (2008) describes a wide range of models that can be used for estimating loads, providing source load estimates, and evaluating various management alternatives. Project managers should keep in mind that models are data intensive, time-consuming to calibrate and validate, and imperfect. Another complicating factor associated with using models is that, depending on the number and types of pollutants or impacts of concern, multiple models may be required. The costs and benefits of a complex modeling approach must be weighed against the costs and benefits of other approaches that rely on simpler spreadsheet tools, analysis of existing water quality data, map overlays, and visual observations. USEPA (2008) outlines the various factors to consider when selecting a model. An inventory of watershed models is maintained at Texas A&M University ((TAMU/BOR n.d.).

2.4 TARGET CSAS AND BMP OPPORTUNITIES



The assessment of pollutant pathways and estimates of relative source contributions enable decisions to be made regarding CSAs and BMP implementation strategies. There will be a greater or smaller level of uncertainty about these factors depending on the complexity of the problem, watershed characteristics, availability and quality of data, and the tools and methods used. While it is most desirable to have a tightly defined CSA and BMP implementation plan, the reality is that there will be inefficiencies. Two ways to address uncertainty through adaptive management are:

- Cast a broader net when defining the CSA and incorporate interim milestones in the BMP implementation plan to ensure that water quality goals can be achieved despite uncertainties in watershed plan development and implementation (discussed here).
- Monitor progress in plan implementation to assess the accuracy of CSA delineation, appropriateness of BMP selection, achievement of interim milestones, and water quality improvements (see Section 7).

The delineation of CSAs must encompass a sufficient number of sources and BMP opportunities to ensure that pollutant or impact reduction targets are achieved within a specified timeframe. During the planning phase, projects should specify BMP performance levels needed to achieve water quality goals. Specific BMPs and BMP systems are developed later to address site-specific needs and conditions. Because of uncertainties associated with CSA assessment and BMP selection and planning, as well as the fact that implementation of recommended BMPs and measures is often not guaranteed due to the voluntary nature of many pollution control programs, CSA delineation should include more sources than needed to meet the targets (i.e., a safety factor). As illustrated in Figure 17, a prioritization scheme for selecting those sources and BMPs of first choice should be incorporated within such an approach (see Section 2.4.1 for details on rating source areas). The magnitude of the safety factor should be determined based on an understanding of the assumptions and uncertainties associated with the CSA determination and local knowledge of the likelihood that needed BMPs and measures will be implemented.

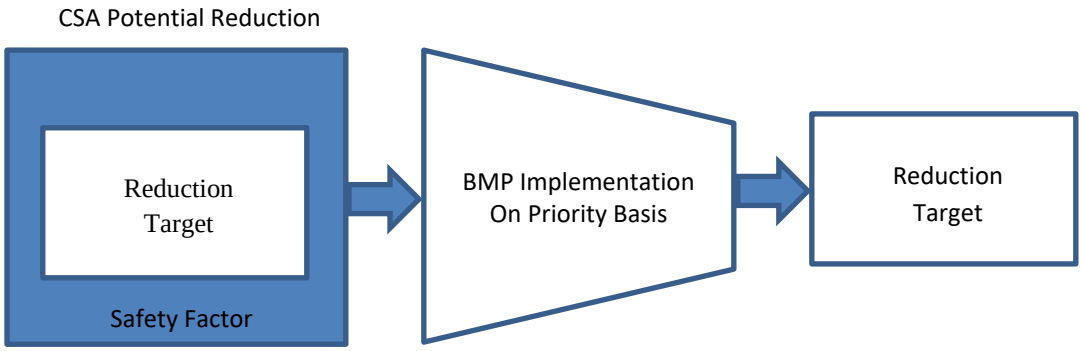


Figure 17. CSA delineation and BMP prioritization to meet targets.

2.4.1 Rate Source Areas

Selection of source areas for inclusion within the CSA is facilitated by development of good estimates of relative contributions to the problem (Section 2.3). Where pollutant load estimates have been generated for each potential critical source or source area, selection can be based on mathematics or a combination of mathematics and factors associated with treatability (i.e., the likelihood that BMPs can be implemented to reduce pollutant loads in these areas). Source treatability factors are described in Section 2.4.2 and incorporate a range of implementation incentives and constraints. See the Upper Maumee River case study for an example rating approach. Regardless of the specific rating system used, the cutoff for inclusion of sources within the CSA should reflect the considerations illustrated by Figure 12.

2.4.2 Examine BMP Opportunities

The focal point for examining BMP opportunities should be the BMP performance levels needed to reduce pollutant loads in the CSAs to the level required to meet water quality objectives. As illustrated in Figure 4, there are multiple intervention opportunities along the pollutant pathways to prevent, capture, eliminate, or transform pollutants. Based on their knowledge of both source magnitudes, current management, and the potential for achieving pollutant reductions from available BMPs and BMP systems, planners should develop alternatives for achieving the CSA reduction target or targets. The plan should incorporate the three basic strategies of controlling pollutant sources, modulating (e.g., peak discharge rates) or eliminating transport of storm water from the site, and treating contaminated water before it is delivered to receiving waterbodies. These strategies should be considered and implemented at both the sub-CSA and CSA-wide scales to ensure that BMPs and BMP systems function together to achieve pollutant reduction targets. The sub-CSA scale may include neighborhoods or small sewersheds in urban areas, or subwatersheds or smaller catchments in rural areas. Specific BMPs and BMP systems should be considered after BMP performance expectations have been determined at the CSA-wide and sub-CSA scales. Clearly, an iterative process will usually be required to ensure that a feasible plan is developed.

As part of this process, projects should establish an inventory of practices and BMP systems that can be used in the watershed to address the pollutants of concern. This list should include the expected performance of each practice

and any known conditions that must be satisfied to achieve that performance level. These conditions may include, for example, applicable land uses (e.g., parking lots), specific site conditions (e.g., well-drained soils), design criteria, and required complementary practices (e.g., treatment trains). The preferred sources of performance information are peer-reviewed literature sources, results from local monitoring efforts, state and local BMP manuals, and similar sources. The best professional judgment of subject matter experts familiar with local watershed conditions should be employed to fill information gaps and aid in the interpretation of literature values. Regional and national information may be used as a starting point when necessary, but the performance of many BMPs is location-specific, so interpretation of performance values from these sources should also be aided by experts.

Major factors to consider when selecting BMPs or BMP systems include (USEPA 2008):

- Whether the site features are suitable for incorporating the practices (i.e., practice feasibility)
- The effectiveness of the practices at achieving loading targets
- Practice cost
- Acceptability of the practices to stakeholders

Site constraints to BMP implementation may include such limitations as compatibility of a candidate practice with a currently installed practice, low infiltration rates, insufficient area available for the BMP (e.g., constructed wetlands), regulatory requirements (e.g., practice installation requires an expensive retrofit of existing practices that will be used as part of a BMP system), or other practice design specifications. CASQA (2003b) notes that selecting development BMPs based on pollutants of concern is a function of site constraints, constituents of concern, BMP performance, stringency of permit requirements, and watershed specific requirements such as TMDLs.

A rating system can be beneficial when making decisions regarding the suite of BMPs and the desired level and location of implementation within the watershed. MARC (2008) developed a rating system for the value of various urban BMPs in terms of water quality value, water volume reduction, temperature reduction, and oils/floatables reduction. An excerpt of the value rating table is shown in Figure 18.

Cover Type or BMP	Median Expected Effluent EMC TSS (mg/L)[a]	Value Ratings				Overall Value Rating
		Water Quality Value	Volume Reduction	Temperature Reduction	Oils/ Floatables Reduction	
Vegetation	N/A	5.25	2	1	1	9.25
Native Vegetation preserved or established						
Rain Garden	< 10	4	2	1	2	9.0
A small residential depression planted with native vegetation designed to capture and infiltrate runoff						
Infiltration Practices	< 10	4	2	1	2	9.0
Infiltration Basin						
Infiltration Trenches						
Bioretention	< 10	4	1.5	1	2	8.5
Small engineered and landscaped basins designed to filter runoff before release						
Pervious or Porous Pavement	10-20	3	1.5	1	2	7.5
Pervious Concrete						
Porous Asphalt						
Modular Concrete Block						
Extended Detention Wetland	< 10	4	2	0	1	7.0
A land area that is permanently wet with hydric soils sized to detain the WQv for a minimum of 40 hours.						
Wetland Swale	10 - 20	3	1.5	0	2	6.5
An open vegetated channel without under drains or soil matrix designed to remain wet between rain events.						

Figure 18. BMP value ratings (Marc 2008).

Factors that should be included in any rating system include:

- Pollutants and problems addressed by the system
- Effectiveness for each pollutant of concern
- Cost to land owner/operator
- Applicability to sources of concern (e.g., capability of land owner or manager, site constraints)
- Implementation approach
- Acceptability, including current implementation rates to demonstrate acceptability
- Other factors unique to the watershed

The Center for Watershed Protection (2012) provides tables identifying a wide range of rating factors, including regulatory goals, land use, physical feasibility, community and environmental factors, and location and permitting considerations.

Scoring can be done in many ways, including a simple check-off of factors suitably addressed, a weighted scoring system, threshold requirements, etc. The result of scoring should be a prioritized list of BMPs or BMP systems, perhaps one for each pollutant or source of concern.

As with CSA delineation, the selection of appropriate BMPs and other measures to achieve pollutant load reduction targets is largely a technical matter. However, because the management tools available to support this implementation include both regulatory and voluntary programs, consideration of the human element is essential. In addition, the permanence of any effort to reduce pollutant loads depends on the good stewardship of land owners and land managers because, even if all BMPs are required under regulatory programs, enforcement tools and resources are often inadequate to ensure proper maintenance and operation of practices.

Types of BMPs

The Center for Watershed Protection grouped different stormwater quality control BMP designs for the District of Columbia into thirteen general categories:

- Green roofs
- Rainwater harvesting
- Impervious surface disconnection
- Permeable pavement systems
- Bioretention
- Filtering systems
- Infiltration
- Open channel systems
- Ponds
- Wetlands
- Storage practices
- Proprietary practices
- Tree planting and preservation

Within each BMP group, detailed performance criteria are presented that govern feasibility, conveyance, pretreatment, treatment, landscaping, construction sequence, maintenance, and stormwater retention calculations.

MARC (2008) identified a range of BMPs that can be used in urban treatment trains, including:

- Vegetation
- Rain gardens
- Infiltration practices (e.g., infiltration basin, infiltration trenches)
- Pervious or porous pavement
- Extended detention wetland
- Native vegetation swale
- Wetland swale
- Bio-swale
- Media filtration practices (e.g., surface sand filter, underground sand filter, pocket sand filter, perimeter sand filter)
- Extended wet detention
- Extended dry detention basin
- Turf grass swale
- Others (e.g., proprietary media filtration devices, hydrodynamic devices, baffle boxes, catch basin inserts)

MARC (2008) encourages developers and site design teams to select a combination of practices to meet basic requirements (e.g., detention), noting that the “right” treatment train best satisfies stormwater management requirements and project goals and offers the most overall value. Preserving native areas or establishing vegetated open space is commonly the first stage of their treatment trains. However, because many suburban or urban sites have land use, design requirements, or other constrains which limit the amount of open space available for stormwater management, engineered stormwater infiltration practices and treatment may also be required. Examples of infiltration practices include pervious vegetated areas, infiltration trenches and basins, pervious

pavement parking lots, and residential rain gardens. Where open space and infiltration practices are not sufficient to manage all runoff from a site because of inadequate space, soils and geology, slopes, or other factors, they recommend adding filtration systems at or near the source of runoff as the next stage of the treatment train. Examples of filtration systems include sand filters, bioretention cells, wetland swales, and vegetated channels. Stormwater detention practices are the last stage of the treatment train. The following examples illustrate possible treatment trains for three types of sites:

- Residential subdivision: (1) preserve native prairie remnant as common open space; (2) landscape with native vegetation; and (3) use dry swales to convey and treat runoff from landscaped streets and yards.
- Commercial development: (1) establish native landscaping in and around buildings and parking areas to break up impervious areas and (2) use bioretention cells in parking lots.
- Office park: (1) place filter strips around building downspouts and parking lots, leading to (2) infiltration basins; (3) use dry swales to treat runoff from streets and convey it to (4) a wet pond.

Agricultural BMPs can be grouped as vegetative, structural, or operational practices, or simply as structural and nonstructural practices (Table 4.). Perhaps the most comprehensive list of agricultural BMPs is contained in the USDA-NRCS Field Office Technical Guide (FOTG) for each state (USDA-NRCS, n.d.).

Table 4. Examples of structural and nonstructural practices (USEPA 2008)

Sector	Structural Practices	Nonstructural Practices
Agriculture	Contour buffer strips	Conservation tillage
	Drainage control structure	Cover crops
	Grassed waterway	Drainage water management
	Livestock exclusion fence	Erosion and sediment control plan
	Sediment basins	Grazing management plan
	Terraces	Irrigation management plan
	Waste treatment lagoons	Nutrient management plan

In its Agricultural Management Practices for Water Quality Protection module, USEPA (2017a) describes the Conservation Technology Information Center CORE 4 practices (conservation tillage, crop nutrient management, pest management, conservation buffers) and four additional management measures (irrigation water management, grazing management, animal feeding operations management, erosion and sediment control) that are basic to controlling NPS pollution from agricultural sources. The New York State Soil and Water Conservation Committee (NYSSWCC 2014) developed a catalogue including a list of agricultural management systems (e.g., prescribed rotational grazing system) by category (operational, structural, vegetative) and lifespan. The descriptions of each of these systems include a definition, water quality purpose, pollutants controlled, where the system is used, system effectiveness, impacts on surface and groundwater, cost, operation and maintenance, and information on cost-sharing opportunities and regulatory requirements.

As is the case for urban BMPs, agricultural practices should be implemented as systems, with consideration given to both sub-CSA and CSA-wide treatment needs. As described in Section 1.1, USDA currently recommends a CMS approach for treatment, and two basic CMS practice combinations have been established for situations with and without manure (Table 1).

Miller et al. (2012) state that, despite difficulties determining the effectiveness of conservation systems due to their complexities and synergies, it is becoming clear that they are more effective than BMPs individually. For

example, conservation tillage reduces loading to buffer strips, increasing the effectiveness of those buffers, but a change in tillage may require different nutrient and pesticide management. Some BMPs will not perform well in the absence of companion practices. Terracing, for example, often requires grassed waterways or a tile system design to function properly. Similarly, contour farming is often paired with contour buffer strips and a conservation crop rotation.

Sharpley et al. (2006) describe BMP systems to reduce P losses at the farm and broader scales. These systems include source BMPs, transport BMPs, and long-term solutions such as advances in crop and livestock breeding, feed processing, and manure utilization. Possible source and transport BMPs for P reduction systems include:

- Source BMPs
    - Feed supplements
    - Feed additives
    - Crop hybrids
    - Manure management
    - Rate of application
    - Timing of application
    - Method of application
    - Source application
    - Crop rotation
    - Manure amendment
    - Soil amendment
    - Cover crops/residues
    - Invert stratified soils
- Transport BMPs
    - Cover crop
    - Conservation tillage
    - Grazing management
    - Soil drainage
    - Stream buffers
    - Strip cropping, contour tillage, terraces
    - Sediment delivery structures
    - Critical source treatment

Management Tools

Best management practices and other measures can be implemented voluntarily or required under a regulatory program. Point sources are most often controlled using regulatory approaches. It is important to consider that regulatory approaches work well only when adequate mechanisms are in place to provide oversight and enforcement. Regulatory programs include:

- Local stormwater ordinances and permits
- Local development ordinances and permits
- Federal or state forest land management plans
- Federal or state grazing permits, state regulatory authorities
- National Pollutant Discharge Elimination System (NPDES) permits for wastewater, industrial discharges, municipal stormwater, and confined animal feeding operations (CAFOs)

- Off-site mitigation banking under Section 404 of the Clean Water Act

The largest voluntary programs include agricultural cost-share programs administered by USDA and states. For example, the Maryland Agricultural Water Quality Cost-Share (MACS) Program provides farmers with grants to cover up to 87.5 percent of the cost to install BMPs to prevent soil erosion, manage nutrients, and protect water quality (MDA 2017). Grassed waterways, streamside buffers, and animal waste management systems are among more than thirty BMPs currently eligible for cost-share grants.

Other incentives are offered as well. For example, the Virginia Resource Management Planning program promotes voluntary use of conservation practices that improve farming operations and water quality (Virginia DCR 2017b). Implementation of a certified resource management plan (RMP) provides plan holders with assurance of compliance with any new state nutrient, sediment, and water quality standards, including regulations related to the Chesapeake Bay and all local stream segment TMDLs. The certificate of safe harbor is valid for nine years provided the farmer continues to implement the RMP. Participants can choose to have an RMP on the whole farm, a tract, or just one field, and RMPs can be developed for crop, hay, or pasture land uses. All RMPs must contain a nutrient management plan and a soil conservation plan. Crop and hay land require a 35-foot forested or vegetative buffer adjacent to perennial streams, while pasture fields must have livestock excluded from perennial streams, hardened stream crossings, and alternative watering systems. The RMP program is a four-step process:

- Assessment – A certified RMP developer meets with the farmer and evaluates the land and practices in place.
- Plan Development – The certified RMP developer discusses plan options with the farmer. After the farmer agrees to the set of BMP(s) and an implementation schedule, the RMP may be submitted to the review authority (the local soil and water conservation district or DCR) for review and approval.
- Plan Implementation – After the approved plan has been fully implemented, the review authority visits the farm to verify implementation. A certificate of RMP implementation is issued if full implementation is confirmed.
- Verification – Farm visits are conducted every few years to ensure the continued proper functioning and maintenance of the BMPs.

The Nature Conservancy (TNC 2017) and other non-profit organizations and industry groups have cooperated with the agriculture community on many watershed and BMP projects. For example, TNC, Sheboygan County conservation staff, and other public agencies and private organizations have partnered with landowners and farm operators in Sheboygan County under the Wisconsin Buffer Initiative to target conservation practices on those fields and pastures with the greatest potential for contributing nutrients to streams.

Funding is currently one of the greatest challenges facing local communities as they implement urban BMPs. USEPA has provided information regarding various funding options for green infrastructure and stormwater programs (USEPA 2017b). Funding source categories include taxes/general funds, fees, stormwater utilities, credits/incentive programs, bonds, grants, loans (e.g., State Revolving Fund), and public–private partnerships. Urban watersheds present some unique challenges with respect to determining whether or not proposed projects are eligible for grants. This is because of the potential overlap with NPDES permits issued to MS4 (municipal separate storm sewer system) jurisdictions. For example, projects and activities required by an MS4 permit are not eligible for Clean Water Act §319 grant funding. General supplemental guidance has been prepared by USEPA that provides some clarification on the §319 funding eligibility question (USEPA 2003). However, decisions have typically been made on a case-by-case basis.

By working with representatives from available programs, watershed managers may find opportunities to tweak these programs to address their BMP implementation needs. Such opportunities could include changing the set of BMPs supported through the program, altering BMP design specifications, providing incentives for preferred BMPs, targeting efforts to specific watersheds or CSAs, or simply more aggressive outreach to increase BMP adoption.

Assessing Current Level of Management

The need for additional BMPs and other measures cannot be assessed accurately unless information is available regarding the current level of BMP implementation, operation, and maintenance. This baseline information can be developed from agency records, land owner/manager surveys, windshield surveys (e.g., Hill 1998), aerial imagery, and communication with local stakeholders. Given that planning should occur at both the CSA-wide and sub-CSA levels, it is necessary to consider BMPs and BMP systems for each location within the context of what the conditions are at adjacent locations that may share the same pollutant pathways. In other words, current management status should be assessed at both the site-specific and landscape scales to provide a more complete picture of treatment needs.

Assessment of the effectiveness of current BMPs and other measures is challenging without definitive monitoring data, a common occurrence. Verification that these BMPs are in place and functioning can be performed in several ways, including the BMP verification methods developed and applied in the Chesapeake Bay Watershed (Chesapeake Bay Program 2014b). These verification methods address urban sources, forestry sources, agricultural sources, wastewater treatment, wetlands, and stream restoration. Methods developed for urban sources were presented separately for BMPs located in MS4 areas and non-MS4 areas, non-regulatory BMPs, and legacy BMPs. For example, non-regulatory BMPs are defined as those BMPs that are voluntarily installed in a community, including homeowner BMPs that are installed on private land (e.g., rain gardens, permeable pavers, downspout disconnection, etc.). For these BMPs, the actual installation of each homeowner BMP must be field-verified by the local government or designated third party at the time of construction, and BMPs submitted by homeowners must be validated by spot-checking them against typical default values for the practice. An alternative approach would be to have homeowners submit digital photos to confirm their practices, with the final decision on BMP condition made by the locality.

Three BMP categories were established for agricultural verification (Chesapeake Bay Program 2014b):

- Visual assessment BMPs - Single Year (e.g., conservation tillage, cover crops)
- Visual assessment BMPs - Multi-Year (e.g., animal waste management systems, streamside buffers)
- Non-visual assessment BMPs (e.g., nutrient management, poultry litter transport)

The mechanism for BMP funding and implementation was also factored into decisions regarding appropriate verification methods, with the following categories established:

- Non-cost-shared (privately funded) BMPs
- Cost-shared BMPs
- Regulatory programs
- Permit-issuing programs

The set of verification methods that can be applied to agricultural BMPs include:

- Farm inventory

- Office/farm records
- Transect survey
- Agency-sponsored surveys
- Remote sensing

Matrices were developed to indicate which methods could be applied to each BMP category and funding/implementation category. For example, review of existing office records by trained and certified federal, state, or county agency personnel with no on-site verification could potentially be used to verify the presence of conservation tillage and the implementation and expiration dates, but could not be used to verify whether its implementation meets practice standards and specifications.

Visual observation, including measurements and relevant calculations, is generally the preferred verification method. Some practices, such as cover crops, require multiple observations to assess whether the practice was implemented and likely to be functioning properly. Cover crops are checked in the fall to determine species, estimated establishment date, establishment density, planting method, and manure application, and again in late spring to confirm cover crop species and termination method. Information on data sources useful for this task can be found in Section 5.5.

Urban BMP Opportunities:

Urban stormwater BMP planning typically involves an array of implementation strategies, both constructed runoff volume reduction practices and the use of natural areas. Major considerations include feasibility, constraints, potential effectiveness, and associated benefits. An important component of the options assessment is identifying the amount and type of impervious area that can be directed to a BMP.

Desktop analyses can provide estimates of the relative benefit derived from various management practices applied in CSAs. Specifically, desktop analyses can be used to evaluate relative BMP performance given the array of sizing options (e.g., bioretention media depth, amount of area retrofitted, etc.) and the range of design assumptions (e.g., native soil infiltration rates). Urban stormwater BMPs to achieve stream flashiness and volume reduction targets include bioretention, infiltration, vegetative conveyance, and permeable pavement.

Preliminary strategies that reflect the level of implementation needs identified for CSAs are often developed through a screening analysis. These strategies should then be examined and compared using criteria that consider proximity to receiving waters, project feasibility (physical suitability of the site, costs, access, easements, location relative to utilities, etc.), costs, design/build time, and maintenance requirements.

Finally, a summary of proposed projects should be prepared that reflects stakeholder input, funding options, and realities associated with scheduling.

Agricultural BMP Opportunities:

As discussed above, USDA is involved in the greatest share of voluntary BMP implementation on agricultural lands. Most technical assistance provided to farmers by NRCS leads to the voluntary development of a conservation plan. A successful plan helps clients achieve their objectives while, at the same time, meet their responsibility to care for the land. NRCS works to assist each client to achieve a sustainable system intended to contribute to healthy bottom lines as well as healthy ecosystems, landscapes, and watersheds.

Based on the conservation plans developed, NRCS and its partners provide the guidance and assistance needed to design, lay out, and install approved conservation practices. There are over 167 approved conservation practices

designed to fit both the resource needs and the land users' objectives. Practices may range from simple management activities such as irrigation water management using state-of-the-art monitoring tools to complex structural practices such as animal waste management systems or innovative irrigation devices.

NRCS delivers conservation technical assistance through its voluntary Conservation Technical Assistance Program (CTA). CTA is available to any group or individual interested in conserving natural resources and sustaining agricultural production in the U.S. This includes farmers, ranchers, local units of government, citizen groups, recreation groups, tribal governments, professional consultants, state and federal agencies, and others. The CTA Program works through a voluntary conservation network that fosters partnerships among NRCS, conservation districts, state conservation agencies, and millions of private landowners. To receive technical assistance, the individual may contact his or her local NRCS office or the local conservation district.

Although the CTA program does not include financial or cost-share assistance, clients may develop conservation plans, which can serve as a springboard for those interested in participating in USDA financial assistance programs. CTA planning can also serve as a door to financial assistance and easement conservation programs provided by other federal, state, and local programs. In addition, recipients of technical assistance under CTA are educated regarding conservation options, thereby increasing opportunities for farmers to implement BMPs with or without financial assistance.

The challenge for watershed managers is to ensure that practices needed to meet pollutant load reduction targets are prioritized and directed to CSAs to the extent feasible through NRCS, state, and local programs. In some cases, this may be accomplished by providing additional incentives (e.g., cost sharing) for those practices of greatest importance to the water quality objective. Another approach would be to work with the agencies and land owners to stage implementation of conservation plans in a manner that addresses BMPs needed for water quality purposes before other practices are implemented. None of this is easy to accomplish because of the broad nature of NRCS conservation plans.

Watershed managers should work with NRCS and its partners at the state and local levels throughout the process of delineating the CSA and selecting BMPs to ensure maximum buy-in and cooperation regarding the selection and placement of agricultural BMPs. Leveraging the Environmental Quality Incentive Program (EQIP) and other programs to achieve targeted implementation of needed BMPs in a cost-efficient manner is a challenge that can only be met through strong collaboration.

USDA is accustomed to ranking applicants for technical and financial assistance, and watershed managers should, if possible, tap into and build upon that process to develop ranking criteria that help drive assistance toward achievement of the pollutant load reduction targets within CSAs. The Missisquoi Bay Critical Source Area Study, for example, concluded that farm-scale ranking of funding applications should be based on site physical characteristics (e.g., slope, topographic index, soil group, proximity to water) and accurate site information on land use and cropping patterns, management practices in place, and soil test phosphorus (STP) obtained by field surveys (IMBSB 2012). It stated that resource management agencies should be proactive in their outreach, targeting landowners where potential CSAs have been identified for the watershed, rather than passively responding to applications for funding.

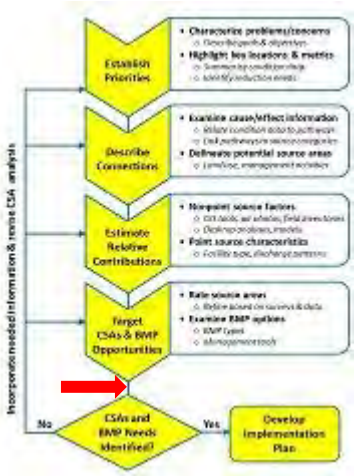
As described for urban BMPs, preliminary strategies should be examined and compared using criteria that consider proximity to receiving waters, project feasibility (physical suitability of the site, costs, access, easements, location relative to utilities, etc.), costs, design/build time, and maintenance requirements. This analysis may be facilitated through cooperation with USDA and its partners.

Estimating Effectiveness of Candidate BMP Scenarios

A final step in deciding on BMP priorities is the merging of strategies for urban, agricultural, and other sources into a single plan. This will only be possible if watershed managers work closely with stakeholders from all sectors throughout the process.

Watershed managers should assess alternative treatment scenarios (e.g., BMPs, source removal) to determine the best alternative for achieving required pollutant or impact reductions or prevention from all applicable sources (e.g., agriculture, urban, hydrologic modification, resource extraction) to achieve water quality goals. Pollutant removal rates can be obtained from several sources including some BMP handbooks (e.g., Miller et al. 2012, CWP 2012) and sources identified in Section 5.6. Tools available for this analysis include watershed models and desktop analysis.

3. Analysis of Sensitivity and Uncertainty



Essential to the process of delineating CSAs and developing and executing BMP implementation plans is an assessment of the validity and importance of assumptions made regarding factors such as infiltration rates, management practices already in place, BMP performance, and pollutant pathways. Because uncertainty is the rule rather than the exception in watershed analyses, all estimates of pollutant contributions should include a margin of error. Quantification of this error is often elusive, and its interpretation can be very complicated, so best professional judgement is required.

According to Donigian and Imhoff (2009), a comprehensive assessment of watershed models includes:

- Consideration of how well a model is able to simulate observed data that describe the watershed's hydrologic and water quality response to its forcing functions (i.e., model calibration and validation).
- Measuring the relative sensitivity of model output to various model parameters in the specific setting in which the model is being applied (i.e., parameter sensitivity).
- Assessing the potential uncertainty that is introduced into model output as a result of naturally occurring variability in the actual values of model parameters (i.e., parameter uncertainty).

Not all models and tools for CSA delineation and BMP selection will require calibration. For example, STEPL (Spreadsheet Tool for Estimating Pollutant Load) is a spreadsheet tool for which calibration is not required (Tetra Tech 2017).

Whether or not the model or tool requires calibration, however, it is fair to assume that all model outputs are wrong to some degree. Any modeling effort (whether complex or based on simple spreadsheet tools) should include a range of estimates that reflect alternative scenarios under which pollutant pathways might differ, source management varies, BMP performance is uncertain, unit-area load assumptions are not accurate, etc. Parameter sensitivity analysis and parameter uncertainty analysis provide both the modeler and those who use the model results with a means of understanding a model's inherent strengths (or limitations) in accuracy (Donigian and Imhoff 2009). An analysis of the sensitivity of the model to identify the most influential parameters in determining the accuracy and precision of predictions is essential. An assessment of parameter uncertainty is also recommended, but this may not be feasible in many cases.

3.1 PARAMETER SENSITIVITY

According to Khalid et al. (2016), sensitivity analysis is an integral part of model development and involves analytical examination of input parameters to aid in model validation. Ellis et al. (2011) presented an approach for sensitivity analysis that reflects the source of parameter default values. In their modeling of mosquitos and disease transmission, they used parameter default values taken from empirical studies for which parameter ranges were rarely provided. For their sensitivity analysis, they set parameter ranges of ±20 percent of the default value based on expert opinion. Exceptions included cases where the empirical range was larger and truncation of the range when the 20 percent rule created impossible values.

Bahremand and De Smedt (2008) performed sensitivity analysis on the spatially distributed hydrologic model WetSpa using a model-independent parameter estimator, PEST, which is a nonlinear parameter estimation and optimization package. Sensitivity analysis was performed to investigate which parameters were sensitive with respect to the available observations, and which were insensitive and could be set to fixed values. PEST does this by adjusting model inputs, running the model, reading the outputs of interest, recording their values, and repeating the computing cycle. The authors caution that the results of such an analysis should be carefully interpreted because sensitivity statistics may depend on the initial parameter values used in the model. They avoided the influence of parameter correlations (e.g., seemingly insensitive parameters that are correlated with other parameters essential to model behavior) by changing the parameters one by one.

Da Silva et al. (2015) conducted sensitivity analysis and calibration of SWAT for application to the Poxim River in Brazil. After using default parameter values for their initial simulation, they used three methods to vary values within upper and lower limits established according to the characteristics of each parameter. The first method modified the initial value of the parameter by adding an increment, the second method used a set multiplier of the initial value, and a different value was substituted in the third method. They calculated this sensitivity as the percentage difference between the output values for simulations with and without the changed parameter value. Best judgment was used to decide that sensitive parameters were those with average percentage differences greater than 0.05.

Both da Silva et al. (2015) and Donigian and Imhoff (2009) reported that the results of sensitivity analysis is project specific, depending on the period considered for the simulation, as well as the specific combination of parameter values that control hydrologic and water quality outputs.

The following steps for performing a sensitivity analysis for parameters are based on a procedure used by Donigian and Love (2007) for calibration of the Hydrological Simulation Program - Fortran (HSPF), but have been modified slightly for broader applicability:

1. Identify the critical model input and parameters, based either on past experience or specific calibration experience for the watershed.
2. Identify reasonable percent perturbations from the calibration values, increases and decreases, for each model input and parameter (e.g., ±20 percent).
3. Assess the resulting changes to ensure the absolute differences in input and parameters are reasonable and appropriate by:
    a. Performing a run using the calibration parameters as a baseline simulation.
    b. Performing additional model runs, with each run representing a single input/parameter change.
    c. Calculating the percent difference from the baseline and the sensitivity factor, defined as the percent change in model output divided by the percent change in input/parameter value. Note

that Da Silva et al. (2015) used the percentage difference between the output values for simulations with and without the changed parameter value as their sensitivity indicator.

4. Rank the model input and parameters by the sensitivity metric to establish those with the greatest impact on model results.

It is important to keep in mind that parameter sensitivity analysis should be performed by changing one input parameter at a time. Several options for changing input parameter values and characterizing parameter sensitivity are shown in Table 5. The sensitivity factor recommended by Donigian and Imhoff (2009) indicates a 1:1 sensitivity when values are near 100 percent, meaning that, for example, a 10 percent change in the input/parameter value produces a 10 percent change in model result. Although the sensitivity factor used by Da Silva et al. (2015) is calculated differently, both approaches require judgment regarding the point at which a model is deemed sensitive to a specific parameter.

Literature values are recommended (Parameter Values A) where such numbers applicable to the watershed are available. In general, however, decisions on how to adjust parameters should be made at the local level based on best professional judgment, experience with the model or spreadsheet tool, and knowledge of the watershed. Effort required to calculate the two sensitivity indicators (A and B) is minimal compared to that required to run the various scenarios, so both are recommended. Other useful indicators may also be available to improve understanding of how changes in parameter values affect model outputs.

Table 5. Options for parameter values and indicators for parameter sensitivity analysis

Method	Source
Parameter Values A: Set range based on range found in the literature	Ellis et al. 2011
Parameter Values B: Set range at a fixed percentage (e.g., ±20% of the initial value)	Ellis et al. 2011
Parameter Values C: Add (subtract) an increment to the initial parameter value	Da Silva et al. 2015
Parameter Values D: Multiply the initial value by a fixed factor	Da Silva et al. 2015
Parameter Values E: Substitute the initial value with a different value	Da Silva et al. 2015
Sensitivity Indicator A: Percentage difference between the output values with and without the changed value: Sensitivity = (Default Value – Changed Value)/Default Value Sensitive parameters have values >0.05.	Da Silva et al. 2015
Sensitivity Indicator B: Ratio of % changes in model output to input: Sensitivity = (% Change in Model Output)/(% Change in Parameter Value) Values near 1 indicate high sensitivity to parameter.	Donigian and Imhoff 2009

3.2 Parameter Uncertainty

Donigian and Imhoff (2009) recommend assessing the uncertainty in the calibrated model caused by uncertainty in the estimates of the model input parameters after calibration and parameter sensitivity analysis are completed. They note that a formal uncertainty analysis for watershed model applications is uncommon due to the complexity and computational demands of most watersheds that are modeled. Their streamlined approach identifies key parameters using a sensitivity analysis and focusing the assessment on model uncertainty associated with those parameters. Still, parameter uncertainty analysis is beyond the reach of most watershed project staff.

While a Monte Carlo analysis may be recommended for parameter uncertainty analysis (Zheng and Han 2016, Donigian and Imhoff 2009), input and computer capabilities necessary for such an analysis are often not available. Readers are referred to Donigian and Imhoff (2009) for a detailed discussion of the Monte Carlo methodology and procedures they used in their Housatonic River HSPF application.

3.3 EXAMPLE

The following example using the STEPL spreadsheet tool is intended to illustrate some of the approaches described for parameter sensitivity analysis, but is not to be interpreted as a recommendation to use STEPL for CSA delineation and BMP selection. The appropriate tool for any given watershed is a site-specific matter. See Section 6 for a discussion of tools.

STEPL was used to perform parameter sensitivity analysis on five parameters for a fictitious watershed with seven contributing areas. Cropland is the primary land use throughout, but Area 4 has 42 percent urban land. The modeling was performed to assess the baseline condition as part of CSA delineation. It was assumed that some BMPs were already being implemented, primarily nutrient management on cropland. The parameters of concern for this testing are soil P concentration, runoff P concentration, BMP effectiveness, the percentage of cropland under BMPs (nutrient management), and the annual rainfall. Ranges of ±20 percent of the initial input parameter values were tested one by one. For example, if the nominal value for percentage of cropland under nutrient management was 50 percent, values of 40 and 60 percent were also used in model runs. The parameter sensitivity indicators selected are A and B from Table 5, and the annual P load estimate is the STEPL output of interest. Table 6 shows clearly that the estimate for annual rainfall is the most important of the assessed parameters in terms of its effect on P load calculations, while runoff P concentration is second in importance. The influence of these two parameters on P load calculations varies, however, across the seven contributing areas, with the greatest influence seen in Area 7 for annual rainfall (A=35.94, B=1.80) and in Area 3 for runoff P concentration (A=16.76, B=0.84). Note that both indicators yielded this same result, with maximum values for these parameters in these two areas. Because the model has differing sensitivity to these parameters across the seven contributing areas, assumptions made regarding input values may have an impact on CSA delineation decisions.

Table 6. Example parameter sensitivity analysis results

Parameter	Indicator[1]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Watershed
Soil P Concentration	A	4.35	4.59	2.30	8.93	3.37	3.58	3.17	3.74
	B	0.22	0.23	0.12	0.45	0.17	0.18	0.16	0.19
Runoff P Concentration	A	14.19	14.90	16.76	10.17	13.85	14.72	13.16	14.17
	B	0.71	0.74	0.84	0.51	0.69	0.74	0.66	0.71
BMP Effectiveness	A	5.21	4.53	2.16	2.07	7.86	2.58	2.84	5.07
	B	0.26	0.23	0.11	0.10	0.39	0.13	0.14	0.25
%BMP Coverage on Cropland	A	3.17	3.91	0.48	1.25	2.28	1.29	1.50	2.31
	B	0.16	0.20	0.02	0.06	0.11	0.06	0.07	0.12
Annual Rainfall	A	31.16	29.81	30.67	18.96	34.57	33.05	35.94	33.07
	B	1.56	1.49	1.53	0.95	1.73	1.65	1.80	1.65

[1]Sensitivity indicators A and B from Table 5

Taking this analysis a step further, four scenarios were run to determine the range of P loads for each area using a combination of maximum and minimum values for runoff P concentration and annual rainfall. Note that this is a very simplistic approach intended only to illustrate how parameter sensitivity could affect P load calculations. While Table 7 indicates no important shift in the share of the P load derived from each area under the four scenarios, both the total load and load from each area have wide ranges. The importance of this range would depend largely on the target load for the watershed. The extent of the CSA and the selection of BMPs could be

quite different for either end of the range. Keep in mind that the estimates in Table 7 were based on changes in runoff P concentration and annual rainfall of ±20 percent. Different assumptions could yield substantially different results, underlining the importance of using best professional judgment in both performing the parameter sensitivity analysis and interpreting and applying the results.

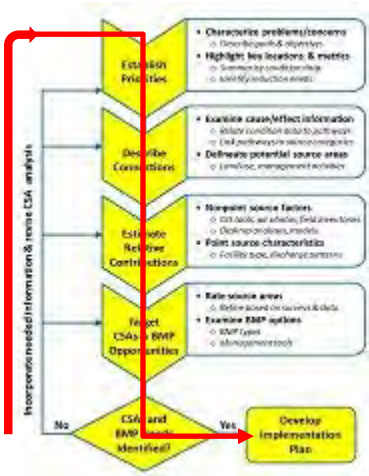
Table 7. Potential range of phosphorus load estimates for STEPL example

Area	Min P Load	Min P Load %	Max P Load	Max P Load %
W1	1,571	12	3,717	11
W2	2,286	17	5,349	17
W3	80	1	199	1
W4	104	1	181	1
W5	4,498	34	11,301	34
W6	3,042	23	7,555	23
W7	1,600	12	4,072	13
Total	13,181	100	32,374	100

As described in Section 1.1, adaptive management incorporating interim milestones is essential to achieving water quality goals. Contingency plans should reflect the uncertainties in the CSA delineation and estimates of relative pollutant contributions. For example, if available information and tools are insufficient to provide reliable estimates of pollutant reductions, interim milestones for that source or category should be included in the watershed management plan. Progressive implementation of BMPs can then proceed as needed to achieve water quality goals.

4. Revising CSA Determinations

CSA identification is an iterative process much like development of watershed plans. As choices are made regarding the various elements of CSA delineation, a reassessment is required to ensure that pollutant reduction targets can still be achieved within a specified timeframe. Decisions regarding BMP performance expectations are a major factor affecting CSA delineation. In a simple sense with all things being equal, lower BMP performance expectations will result in larger CSAs to achieve fixed pollutant reduction targets. Further, if pollutant reduction targets cannot be achieved for certain source categories or sub-areas within the CSA with available BMPs, there may be a need to adjust CSA delineation to include a greater proportion of these sources. Alternatively, it may be possible to rely more heavily on other sources for which selected BMPs will be more successful in achieving performance expectations and reaching the pollutant reduction targets.



In the end, it will be beneficial to create a CSA map that identifies where implementation of specific BMPs is needed to achieve the pollutant reduction targets. This map can be used to help guide implementation activities.

5. Data Sources for Identifying CSAs and BMPs

5.1 Watershed Boundaries

USGS maintains a Watershed Boundary Dataset (WBD) that can be accessed to delineate watersheds at various levels (USGS, n.d.). The WBD is delineated and georeferenced to the USGS 1:24,000 scale topographic base map meeting National Map Accuracy Standards. Hydrologic units are given a Hydrologic Unit Code (HUC). As watershed boundary GIS coverages are completed, statewide and national data layers will be made available via the Geospatial Data Gateway (USDA-NRCS, n.d.).

5.2 Water Quality and Flow

Much of the nation's hydrology, water quality, and biological data resides in national datasets accessible on the Internet. Sources include USEPA's STORET, USGS's National Water Information System Web Interface, and USEPA's WATERS information system. States may also maintain their own data and watershed-specific monitoring data may be available from local agencies or groups or academia.

5.3 Land Form, Land Cover, and Land Use

Information on land form, land cover, and land use is essential to any approach for delineating CSAs, whether it be a modeling approach or a desktop analysis. These data can be obtained in various forms (e.g., tabular, GIS) from a variety of federal, state, and local sources. Federal sources include:

- U.S. Geological Survey (https://landcover.usgs.gov/uslandcover.php)
- National Agricultural Statistics Service (https://www.nass.usda.gov/Data_and_Statistics/index.php)
- National Oceanic and Atmospheric Administration (https://coast.noaa.gov/digitalcoast/tools/lca.html)
- U.S. Fish and Wildlife Service (https://www.fws.gov/GIS/)
- U.S. Environmental Protection Agency (https://www.epa.gov/eco-research/multiresolution-land-characteristics-mrlc-consortium)

The USDA Natural Resources Conservation Service (NRCS) maintains soil geographic databases such as the soil survey geographic (SSURGO) database and the Digital General Soil Map of the United States (STATSGO2). Digital elevation data are available from USGS and NOAA's Digital Coast. The Global Land Cover Facility at the University of Maryland provides a range of earth science data and products, and universities such as MIT provide links to land use and land cover data sets. See USEPA (2008) for a list of sources of GIS data available on the Internet, as well as a discussion of challenges and pitfalls associated with using GIS. While GIS can be very useful and allows for easy display and evaluation of a variety of watershed characteristics, users need to know how to deal with data having different map projections, scales, and time frames, and also need to understand how to organize, store, and manipulate the files.

Other sources include aerial imagery from low altitude and satellite imagery. Readily available aerial and space-based remote sensing data sources such as AVIRIS (Airborne Visible/Infrared Imaging Spectrometer), LIDAR (Light Detection and Ranging), and LANDSAT (LAND remote-sensing SATellite) are described by USEPA (2008).

Local knowledge is also important to ensure that unique situations or conditions are not overlooked. For example, information on previous land use in developing areas can be valuable when delineating CSAs, as described by Nowak et al. (2006). They noted that the interaction of a slow variable (e.g., P buildup on farmland now being developed) with a fast variable (e.g., development on P-enriched soils) creates the conditions for exceptional

consequences such as short, intense pulses of P from construction sites during storm events, and flashier releases of P that would not be transported under average hydrologic conditions.

5.4 Meteorological Data

Hourly precipitation data are available from NOAA (n.d.). The sources of the data are approximately 5,500 US National Weather Service (NWS), Federal Aviation Administration (FAA), and cooperative observer stations in the U.S. In addition to these sources, watershed managers should query cooperators regarding the availability of data from other weather stations in the watershed that are not included in NOAA's database.

5.5 Current Level of Management

Information on the current management for both point and nonpoint sources can be obtained from a variety of sources. For example, the USDA's NRCS and FSA maintain much information on agricultural land management. However, because of privacy constraints specified under Section 1619 of the Food, Conservation, and Energy Act of 2008, the ability to obtain farm-specific information is limited. By working with local soil and water conservation districts (SWCDs), however, watershed managers may be able to obtain reliable information regarding the current level and extent of management of agricultural lands. This information can be supplemented in a variety of ways, including online or written surveys, windshield surveys, and aerial photography. It should be noted, however, that these methods provide varying degrees of accuracy and completeness depending on the specific practices of interest. USEPA's Chesapeake Bay Program has provided technical assistance for roadside transect surveys and remote sensing.

Data on the current level of management in urban settings can be obtained from municipalities, including such sources as master plans and stormwater pollution prevention plans. Information from permitted dischargers can be obtained from USEPA and their state and local partners. Basic population data can be found from the U.S. Census Bureau.

A wide range of information is also available from EPA's Envirofacts website (https://www3.epa.gov/enviro/). This site provides access to data on air, water, the land, wastes, toxics, and radiation. For example, the Permit Compliance System (PCS) provides information on companies that have been issued permits to discharge waste water into rivers. Available data include information on when a permit was issued and expires, how much the company is permitted to discharge, and the actual monitoring data showing what the company has discharged. The Enforcement & Compliance History Online (ECHO) tool provides access to enforcement information for larger and many smaller facilities regulated as Clean Air Act (CAA) stationary sources, Clean Water Act (CWA) permitted dischargers (under the National Pollutant Discharge Elimination System (NPDES), and Resource Conservation and Recovery Act (RCRA) hazardous waste sites.

5.6 BMP Effectiveness

EPA has published national and regional documents on BMP effectiveness that address agriculture, urban areas, forestry, marinas, recreational boating, hydromodification, wetlands, and riparian areas (USEPA, n.d.). State BMP manuals are also widely available.

The International Stormwater BMP Database features over 600 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications (International Stormwater BMP Database, n.d.). There are also plans for a stream restoration database and various reports on urban and agricultural BMPs.

The national and state-specific conservation practice physical effects (CPPE) documents provide guidance from NRCS on the effects that agricultural conservation practices will have on soil, water, air, plants, animals, and human resources.

5.7 Biological Data

The USFWS maintains information on Threatened and Endangered Species final critical habitat designations, National Wetlands Inventory data, and other data and information related to wildlife. In addition, states routinely collect biological monitoring data that can be incorporated into CSA analyses.

6. Tools

A large number of watershed models and spreadsheet tools of varying complexity are available for delineating CSAs and assessing alternative BMP implementation scenarios. Models can range from complex physically-based models such as HSPF (Hydrological Simulation Program - Fortran) that simulate hydrology to simpler export-coefficient based models (Johnes 1996). As noted above, USEPA (2008) describes models that can be used for estimating loads, providing source load estimates, and evaluating various management alternatives. In addition, Texas A&M University maintains an inventory of precipitation-runoff models, hydraulic models, river and watershed management models, GIS applications in hydrology and hydraulics, and stochastic models (TAMU/BOR, n.d.).

However, the mere availability of complex models and tools is insufficient reasoning for deciding to rely on them when delineating CSAs and developing BMP implementation plans. Models can be helpful in filling information gaps or combining various sorts of data to simulate potential outcomes from precipitation events or watershed management actions. In short, models can be useful tools, but the need for a model should be assessed on an individual project basis. In simple terms, models should be considered when simpler, less expensive approaches fail to provide the information needed to make reliable decisions on CSA delineation and BMP implementation plans. If available data, streamwalk findings, and desktop analyses are sufficient to identify with acceptable confidence the sources that need to be treated and the BMP systems to be used to achieve pollutant reduction goals, then there is no compelling reason to invest in a model for this purpose.

In their assessment of NIFA-CEAP, Osmond et al. (2012a) noted the complexity of watershed models and cautioned against placing too much faith in them, stating that the scientific basis of modeling is still evolving. There are many deficiencies in our knowledge and in existing modeling tools for representation of critical natural processes and key management actions at the watershed scale. In general, the complexity and nonlinear nature of watershed processes overwhelm the capacity of existing modeling tools to reveal the water quality impacts of conservation practices. Also, not all conservation practices could be adequately represented in the models. Finally, due either to problems in the modeling or with the water quality data, or both, the models grossly overestimated the effectiveness of conservation practices. Where models are used, they recommend selecting the correct model(s) and modifying them to suit watershed characteristics if necessary. Successful modeling requires sufficiently trained personnel, well-calibrated models, and adequate water quality and land treatment data, including spatial and temporal changes of these data.

Specialized tools may also be available for specific issues, sources, or BMPs. For example, the Chesapeake Bay Program developed a methodology for estimating BMP efficiency for onsite waste disposal systems that is transferable to other locations (Adler et al. 2014). NRCS has developed a national CPPE tool for selecting conservation practices (USDA-NRCS, n.d.). Wan et al. (2014) developed a sophisticated approach for identifying optimal sites in southern Minnesota for constructed wetlands to intercept nonpoint source nitrogen. Their method

uses high-resolution light detection and ranging (LiDAR)-derived digital elevation maps (DEMs), data on subsurface tile drain location, an empirical wetland likelihood model, and the drainage-water management model DRAINMOD.

Ghebremichael et al. (2012) cautioned that watershed simulation models have limitations in delineating CSAs and selecting BMPs because of the disconnect between watershed modeling scales and the farm scale at which BMPs are selected and implemented. Integration of watershed- and farm-scale modeling tools may be necessary to bridge this gap. Challenges include transferring the information acquired from a complex watershed scale model into a simplified form suitable for interpretation by conservation specialists, extension personnel, landowners, and others closely involved with practical aspects of NPS pollution control. Also challenging is the fact that evaluations of CSAs and the impacts of mitigating BMPs are commonly performed using watershed-scale models based on hydrologic boundaries, whereas BMPs are generally selected and maintained at the farm level and are ultimately applied within the field and farm boundaries. In addition, management changes recommended from a watershed or landscape perspective may not be feasible for some farms because each farm experiences unique challenges in balancing various factors of farm production with environmentally-driven management changes.

The importance of proper model or tool selection is illustrated by Giri et al. (2016). They observed that SWAT did not appear to handle well the degree of flashiness caused by the high level of urban impervious surface in their New Jersey watershed. Multiple tools may be required to address the various pollutants of concern in a watershed. Giri et al. (2016) concluded that the ideal CSAs for targeting BMPs varies by pollutant.

When using models, it is important to document the version of the model and the process used for validation and calibration. Performance expectations for the model should be determined in advance and incorporated within a Quality Assurance Project Plan (QAPP). For example, Tetra Tech (2016a) reported that they developed the Sandusky River watershed SWAT model using the ArcSWAT interface and version 591 of the model code. They further noted that they later updated their version of the model to be consistent with the more recent SWAT model code version 637. Model performance was assessed by comparison with criteria set forth in the approved QAPP, which included performance targets for the Nash-Sutcliffe coefficient (NSE), RMSE-observations standard deviation ratio (RSR), and the magnitude of the relative average error (RE). The RE is a measure of the average tendency of the simulated data to be larger or smaller than observed. The NSE is an indicator of a model's ability to predict the timing and magnitude of observed data. RSR can be considered as a normalized error index statistic for which a value of 0 indicates a perfect model.

7. Monitoring Progress

As described above, there are many assumptions, approximations, and uncertainties associated with CSA determination and BMP selection. It is essentially impossible to develop a perfect plan, and even more difficult to ensure complete and precise implementation of a watershed plan. For these simple reasons, watershed managers should establish and implement a progress monitoring system to determine if interim BMP implementation milestones and pollutant removal targets are being met on schedule and whether the desired water quality impacts are being achieved.

Monitoring for load estimation is described briefly in Section 2.3.3. Many watershed projects will not be able to afford comprehensive water quality monitoring efforts to track pollutant loads over time at multiple key locations in the watershed. While watershed models have been commonly used to estimate pollutant loads from alternative BMP treatment scenarios, they should not be used to estimate load reductions for direct comparison with pollutant load reduction targets. Nor should inadequate water quality monitoring (e.g., monthly grab samples and

instantaneous flow measurements) be used to calculated measured pollutant loads. In cases where pollutant loads cannot be estimated with suitable confidence, projects should focus their monitoring efforts on BMP implementation. As described in Section 2.4.2, guidance is readily available for determining the presence of BMPs and whether they have been implemented, maintained, and operated to applicable standards and specifications. By tracking implementation against interim milestones, project managers will know if the plan is being executed properly even if they don't know the resulting pollutant load reductions.

Biological monitoring or tracking of other indicators related to the pollutant load reduction targets may be helpful in demonstrating whether there is an impact on water quality. For example, the Long Creek Section 319 NNPSMP project in North Carolina accessed data from the local municipality on dredging at the water quality intake pool as an indicator of sediment load from eroding cropland (USEPA 2011). At the start of the project, the water supply intake pool had to be dredged quarterly to maintain adequate storage volume, but by the end of the project the frequency of dredging had been reduced to less than once per year.

In accordance with an adaptive management approach, progressive implementation of BMPs and BMP systems can be triggered based on monitoring results that indicate that initial efforts to implement priority BMPs and BMP systems failed to achieve pollutant load reduction targets. If it is shown that BMP performance expectations cannot be met or that reduction targets cannot be achieved within the existing CSA, revisions to the CSA delineation should also be considered. In cases like the Garvin Brook RCWP project, CSA determination may have fatal flaws that are only revealed as additional data are collected. As described in Section 1.1, this project shifted its focus from surface water to groundwater, resulting in a 50 percent increase in the size of the CSA (Wall et al. 1992).

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CASE STUDY: UPPER MAUMEE RIVER, OHIO

This watershed plan combined water quality data and inventory information with a pollutant load analysis, and developed a refined CSA analysis using a tiered approach (Tetra Tech 2016b). The first tier prioritized subwatersheds based on general ratings determined from land use composition and monitoring data. In addition to the quantity and density of agriculture, land use factors considered included the amount of development (urban reduction) as well as the amount of forest and wetlands (protection). A land use composition bar chart (Figure 19), organized by HUC-10 subwatershed, provided a starting point that was used to identify priority areas for implementation planning. For example, the quantity and density of agricultural land use pointed to the Upper Maumee, South Turkeyfoot Creek, the Napoleon area, and Beaver Creek as locations that warranted additional analysis.

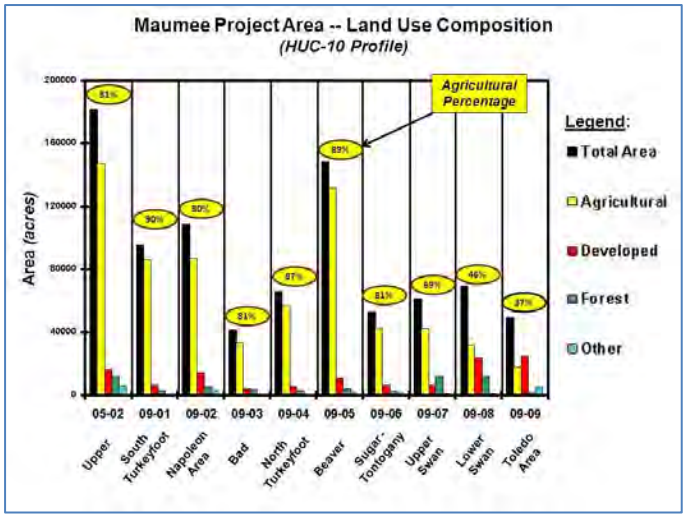

Figure 19. Land use composition.

The CSA analysis was further refined using a data-driven approach at the subwatershed scale. Data collected by Ohio EPA showed the variation of phosphorus concentrations in tributary streams across the Maumee watershed. Sample results were grouped by HUC-10 subwatershed and displayed by HUC-12 units within each group (Figure 20). Similar to the land use analysis, the same subwatersheds (Upper Maumee, South Turkeyfoot Creek, the Napoleon area, Beaver Creek) remained priority areas based on the water quality data. A subset of these HUC-12 units was identified for additional examination to refine the assessment as part of the implementation plan.

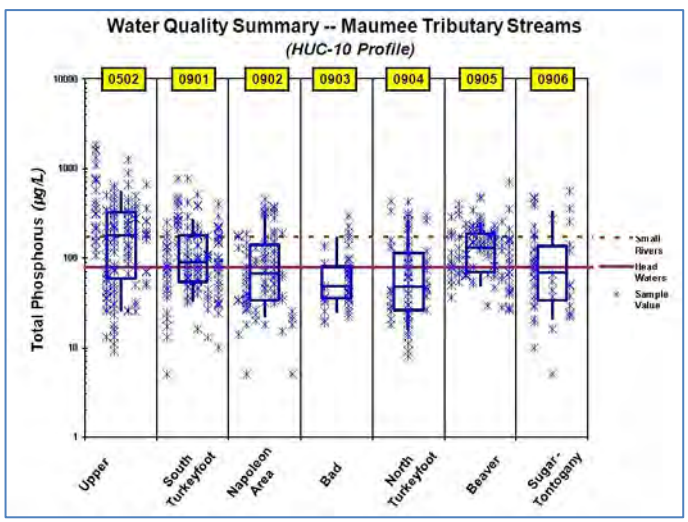

Figure 20. Water quality data used to refine critical area analysis.

General management strategies were categorized as NPS reduction, urban sediment and nutrient reduction, altered stream habitat restoration, and high-quality waters protection. Table 8 includes a subset of these needs. Each strategy plays a key role in determining potential management tools needed to address water quality problems in each subwatershed. For NPS reduction, management tools in CSAs could include a focus on special funding and added technical service support. Management tools in priority subwatersheds focused on urban sediment/nutrient reduction include the use of MS4 permits and stormwater management programs.

Table 8. Subset of Maumee subwatershed implementation strategy rating

HUC-12 *(041000)*		**Name**	**Implementation Strategy Rating**			
			NPS Reduction (e.g., Ag)	*Urban Reduction*	*Habitat Restoration*	*High Quality Protection*
05-02	03	Marie DeLarme Creek	◗	○	○	○
	04	Gordon Creek	◗	◗	○	○
	06	Platter Creek	●●●	○	○	○
	07	Sulphur Creek-Maumee River	◗	◗	○	○
	08	Snooks Run-Maumee River	◗	◗	○	○
06-06	04	Buckskin Creek-Tiffin River	◗	●●●	◗	○
07-12	09	Eagle Creek-Auglaize River	◗	●●●	●●●	○
09-01	02	Upper South Turkeyfoot Creek	●●●	○	○	○
	04	Middle South Turkeyfoot Creek	●●●	○	○	○

Notes: ●●● High priority strategy ◗ Medium priority strategy ○ General benefit

A multi-scale framework (Figure 21) was used in the second tier of the CSA analysis to identify priority catchments within the priority HUC-12 subwatersheds that contribute disproportionate amounts of pollutant load to water quality impairments. The multi-scale framework enabled an evaluation of sources at a level detailed enough to describe specific implementation actions and responsibilities within CSAs.

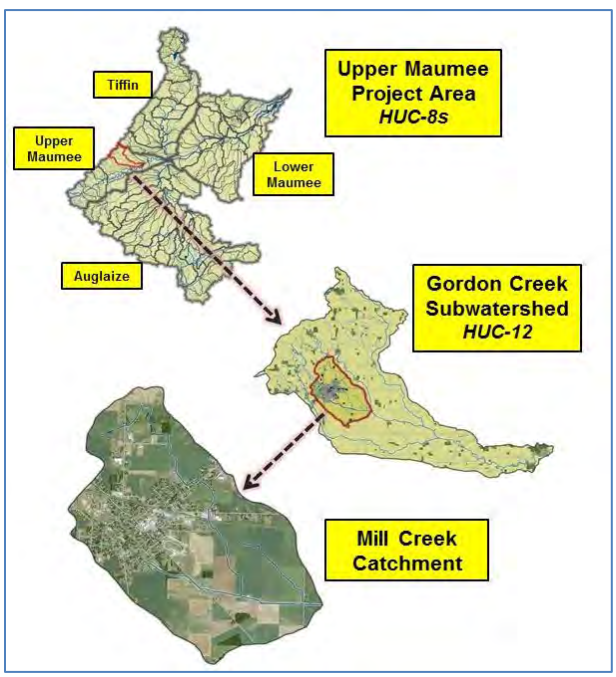

Figure 21. Multi-scale analysis framework.

The CSA for Gordon Creek is shown in Figure 21; it was determined using information from the windshield survey and "desktop screening" that identified implementation opportunities. The subwatershed was delineated into several catchments, enabling the analysis to prioritize locations within the upper Maumee that would provide the greatest benefit in reducing phosphorus loads. CSAs for implementation activities in the Gordon Creek subwatershed were in the Mill Creek catchment. Soil types, topographic slope, land use, and hydrologic connectivity were assessed to determine that this catchment contributed a disproportionate amount of pollutant load to Gordon Creek.