Source Water Assessment and Protection: Research and Sound Science Strategy

Final

Prepared by:
The Cadmus Group, Inc
Arlington, VA 22209

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Jim Goodrich, U.S. EPA, Office of Research and Development
Fred Hauchman, U.S. EPA, Office of Research and Development
Bob Hultquist, California Department of Health Services
Maggie Javdan, U.S. EPA, Office of Research and Development
Bob Masters, National Ground Water Association
Dan Sullivan, U.S. EPA, Office of Research and Development

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Introduction

The United States enjoys some of the highest quality drinking water in the world. Source water protection (SWP) offers a common sense approach to maintaining that quality and safeguarding public health by taking action to protect each source of drinking water before contamination occurs.

Protecting drinking water supplies begins with source water assessments. For every public water system, states are assessing areas that serve as sources of drinking water, identifying actual and potential threats to those sources, and determining the susceptibility of the water supply to those threats. Using information from the assessments, local decision-makers can develop or refine existing management measures to address actual and potential threats through the adoption of best management practices (BMPs). The completed assessments will allow source water protection managers to make the most rational decisions possible to address the highest priority threats to water supplies. Source water protection is an ongoing process: monitoring to detect contamination as early as possible, managing new potential sources of contaminants, and planning for quick response round out an effective SWP effort.

Source water protection is important because it makes good public health, economic, and environmental sense.

- **Public Health.** Though rare, illness can occur as a result of waterborne pathogens, and long-term exposure to certain contaminants in drinking water. Source water protection is the first barrier to keep contaminants out of the source water and drinking water.

- **Economic Benefit.** Drinking water contamination can mean curtailment of business activities and lost wages, medical costs, expensive treatment, and purchase of alternative water supplies. An EPA analysis of several communities showed that on average, dealing with contamination of their ground water supply may be 30 to 40 times more costly than a prevention program (EPA, 1996).

- **Environmental Protection.** Taking actions to protect drinking water sources also protects the water resource for aquatic ecosystems. Development pressures, polluted runoff from agricultural, commercial, and industrial sites, septic system effluent, and aging waste water infrastructure are some of the threats to water quality that affect not just drinking water quality but aquatic habitat.

Not all contaminants can be adequately treated using conventional drinking water system treatment. This is why detecting these pollutants before they enter the drinking water supply is an important safeguard. For example, monitoring networks on the Ohio and Mississippi river systems can detect carcinogenic or toxic compounds in source water; this information would allow drinking water systems along the rivers to take early steps to address the threat without applying expensive treatment or putting public health at risk.

Recent events, including the terrorist attacks of September 11, 2001, and the anthrax attacks later that year, have illustrated the potential for threats to our drinking water supply. While it is generally believed that the likelihood of terrorists contaminating the water supply is low, and water systems have historically been vigilant in protecting public health, these events illustrate the importance of being aware of existing threats, detecting contaminants, and responding quickly if needed.

Contaminants in ground or surface water can affect aquatic plants and animals. Besides the direct effect on these species, some contaminants can be carried up the food chain, and eventually may affect human food supplies as well.

Monitoring cannot be considered a sufficiently preventative measure, since not all contaminants are screened and not all river reaches are monitored. Therefore, preventing contaminants from entering source water is a more effective means to safeguard our drinking water and public health.

Increased understanding of public health concerns from microbiological contamination and disinfection by-product (DBP) formation shows that relying solely on treatment may not be the most effective approach. The best course of action is to promote land use practices that minimize source water contamination rather than rely on treatment alone.

From assessment to prevention, source water protection is a valuable public health, economic, and environmental tool. The information needed to carry out an effective SWP program encompasses the work undertaken in many scientific disciplines. Much work has been done to date since passage of the Safe Drinking Water Act (SDWA) in 1974.

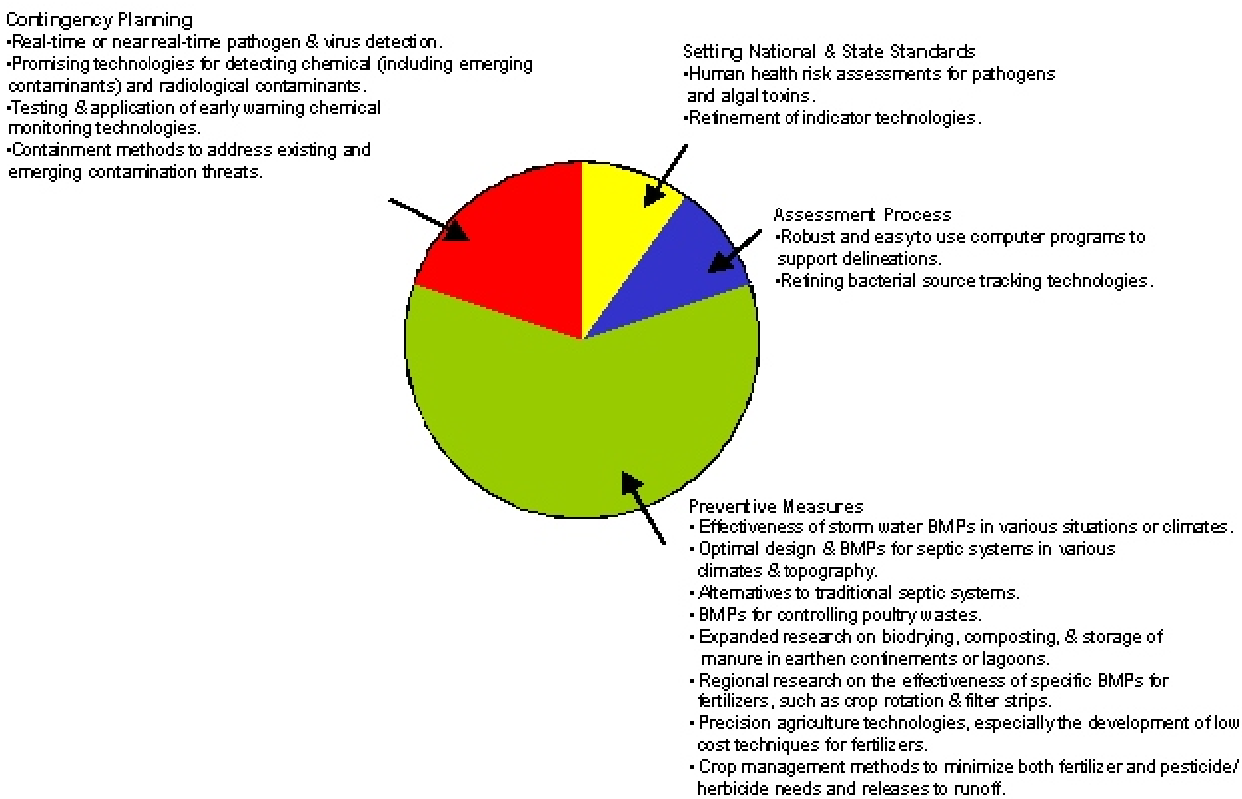
To move forward, it is necessary to determine what research still needs to be done to answer several key questions. This source water research plan presents research questions that define the scientific needs for adequately planned and managed source water assessment and protection programs.

National Research Priorities

EPA identified approximately 60 research needs across the national source water assessment and protection program areas—water quality standards setting, source water assessments, preventive measures to address sources of contamination, and contingency planning. EPA's methodology for determining the priority needs is presented below. These priority research needs cross all of the national SWP program areas—some, such as monitoring and detection technologies, relate to several program areas. The majority of the needs are related to preventive measures, followed to a lesser extent by needs for specific research associated with contingency planning, conducting source water assessments, and standards setting (see Exhibit 1).

Of these, 17 are considered to be national priority needs. One of the 17, "fertilizer use by and effectiveness of outreach programs to homeowners and non-agricultural users" is considered social science research, and is not included in the exhibits below. This critical research is typically accomplished by research organizations outside of EPA.

Exhibit 1: Priorities for Source Water Assessment and Protection Research by Program Area



These research activities would offer a variety of benefits, such as furthering the scientific needs to meet goals and requirements under the Clean Water Act (CWA) *and* the SDWA, benefitting both ground water and surface water supplies, saving money by reducing monitoring and treatment costs, and protecting public health, especially from acute health effects (see Exhibit 2).

Note: A score of at least 13 on a scale of 18 was needed to make this list (see Table 1).

Exhibit 2: Benefits from Priority Source Water Assessment and Protection Research

		Core SWP					
		CWA & SDWA	Ground & surface water	Reduce costs	Improve public health	Acute health benefits	Broader applicability
SETTING NATIONAL AND STATE STANDARDS							
1	Human health risk assessments for pathogens and algal toxins.						
2	Refinement of indicator technologies.						
SOURCE WATER ASSESSMENT PROCESS							
3	Robust and easy to use computer programs to support delineations.						
4	Refining bacterial source tracking technologies.						
PREVENTIVE MEASURES AGAINST VARIOUS SOURCES OF CONTAMINATION							
5	Effectiveness of storm water BMPs in various situations or climates.						
6	Optimal design and BMPs for septic systems in various climates and topography.						
7	Alternatives to traditional septic systems.						
8	BMPs for controlling poultry wastes.						
9	Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.						
10	Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips.						
11	Precision agriculture technologies, especially the development of low-cost techniques for fertilizers.						
12	Crop management methods to minimize both fertilizer and pesticide/herbicide needs and releases to runoff.						
EFFECTIVE CONTINGENCY PLANNING							
13	Real-time or near real-time pathogen and virus detection.						
14	Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants.						
15	Testing and application of early warning chemical monitoring technologies.						
16	Containment methods to address existing and emerging contamination threats.						

Key: cross hatched - applicable to only certain aspects of criterion (score =1); checkered - applicable but not widespread contribution to meeting all components of the criterion (score = 2); dark shading - applicable and widespread contribution to satisfying all aspects of the criterion (score = 3). See Table 1.

Based on this ranking, the highest priority research needs for EPA's source water assessment and protection programs include the following:

Setting National and State Standards to Support SWP

- ***Human health risk assessments for pathogens and algal toxins.*** Of the most pressing interest and benefit to source water assessment and protection are those research activities that would improve the science needed to set standards under the CWA for drinking water contaminants in ambient waters. Research into modeling the occurrence of and human exposure to various contaminants such as pathogens and nutrients would further this goal. Priority research for assessing risk from algal toxins includes conducting epidemiological and epizootiological studies to assess exposure to and acute and chronic effects of algal toxins on public health, terrestrial and aquatic animals, determining the parameters which are likely to result in low level chronic occurrence of harmful algal species in water environments, and developing improved detection methods for known toxic algal species. See more under the discussion of research needs on water quality standards on page 5.

- ***Refinement of indicator technologies.*** Indicator technologies can be used to link potential threats to actual contamination. Research is needed to further refine and improve indicator technologies for detecting fecal contamination and other pathogens of specific concern in source waters. Priority research should focus on refining, developing, and validating available analytical methods to detect and quantify fecal and fecal source indicators. See the discussion of research needs on water quality standards on page 5 under research needs.

  Research on human health risk assessment and indicators is a priority because these technologies offer many potential benefits to source water assessment and protection. Accurate source inventories and susceptibility determinations hinge on understanding the location and number of contamination sources in both ground water- and surface water-based drinking water supply areas, and the presence and fate of associated contaminants. These technologies can also be used to support development of more accurate total maximum daily loads (TMDLs). Refining and improving indicator technologies and understanding the occurrence of pathogens offers tremendous benefits for protecting public health, especially from the potential adverse effects of pathogens on sensitive subpopulations such as the elderly, children, or immuno-compromised individuals. It is also important to note that this research would benefit source water assessments and improve contingency planning (see the discussions below). Refining human health risk assessments would also benefit and apply to other environmental standard-setting programs.

Source Water Assessment Process

- ***Robust and easy to use computer programs to support delineations.*** There are many ways in which information technology can improve ground water and surface water delineations. In the past, sophisticated computer modeling tools were solely in the hands of hydrogeologists, whose consulting services were often outside the financial means of smaller ground water systems. One challenge is to put the latest computing technology in the hands of people doing ground water and surface water assessments. See the discussion on research needs related to computer support of ground water delineations on page 11 and surface water delineations on page 13, under research needs.

This research would have great cost-saving implications. Computers and models have increased in sophistication and ease of use, while prices have decreased. Research should be focused on developing robust and easy to use PC-based programs that would allow decision-makers to input as much data as they have and whose delineation output is as accurate as possible based on the hydrogeologic situation, without hiring expensive hydro-geological services.

Improved software, techniques, and training could help land use planners better understand ground water and surface flow. In addition, research into model development should continue to stress the importance of improving the effectiveness of various models. These types of developments can parallel efforts to make models more robust and easy to use. This research would result in improved delineations, and ultimately maximize the health benefits of source water protection programs.

- ***Refining bacterial source tracking technologies.*** Bacterial source tracking (BST) is an emerging science that offers many potential applications for identifying and better understanding sources of fecal bacteria, whether from humans, livestock, or wildlife. Research is needed to refine and develop potential applications of this technology, such as improving the ability of BST to discriminate between specific livestock or wildlife species. Continued research on BST technologies is needed to evaluate available technologies, or build a "toolbox" of source tracking methodologies that allows managers to pick technologies based on the specific situation. See the discussion on research needs related to contaminant source inventories on page 16 under research needs.

  BST can be used to link potential threats to actual contamination and support TMDL development and other management measures to prevent pathogens from entering ground water- or surface water-based water supplies and making large numbers of people, particularly sensitive subpopulations, ill. It can also provide drinking water systems with a means to target monitoring activities and avert expensive treatment.

Preventive Measures Against Sources of Contamination

- ***Effectiveness of storm water BMPs in various situations or climates.*** Many BMPs are available to address storm water runoff, with differing efficiencies based on local factors or contaminants present. A synthesis of the understanding of which BMPs are most effective in various situations (e.g., urban vs. rural) or climates (e.g., cold weather or high rainfall) would be useful to source water protection area managers. See the discussion of research needs related to storm water BMPs in on page 42 under research needs.

  Research on storm water BMPs is important because storm water has the potential to introduce a wide variety of contaminants, including pathogens and nitrates, as well as hazardous substances from vehicles, industry, or construction activities, to both ground water and surface water supplies in every part of the nation. Additionally, the precise number and location of Class V storm water wells is unknown, but is estimated to be large. Storm water runoff is ubiquitous, and many BMPs exist to address the threats posed by runoff; the challenge is to help managers understand which methods are most appropriate and cost-effective in their situations so that measures are adopted and effective.

National priority research needs related to septic systems, or onsite or decentralized waste disposal systems, include the following:

- ***Optimal design and BMPs for septic systems in various climates and topography.*** Research on which available septic system BMPs are the most cost-effective to install and operate in various regions of the country could improve the efficiency of, and potentially reduce maintenance or other costs associated with, septic systems. This could promote adoption of septic system BMPs beyond those specified in health department regulations for homeowners and small businesses that operate septic systems. See the research needs discussion under of BMPs for septic systems on page 45 under research needs.

- ***Alternatives to traditional septic systems.*** Research should also address development of feasible alternatives to traditional septic systems, including composting systems, wetland treatment systems, and bioreactors. Such research should lead to more widespread use of alternatives, particularly in source water protection areas, and in reducing the number of septic systems.

  Septic systems can contribute nitrates, pathogens, and other contaminants to ground water—many of these contaminants require expensive monitoring to detect or costly treatment to remove. Health effects and treatment requirements for some contaminants in septic system waste, such as endocrine disruptors, are not yet well understood. Septic systems may impair surface water as well, which is a concern for CWA programs. Given the large number of septic systems throughout the nation, appropriate design and management of (and possibly alternatives to) the systems is important for controlling a source that has a potentially huge impact to water supplies.

Two priority research needs related to animal feeding operations include the following:

- ***BMPs for controlling poultry wastes.*** Poultry feeding operations are quite pervasive across the country, and research into further application of animal feeding operation BMPs to the specific nature of poultry facilities is considered a priority. Available BMPs worthy of further research include filter strips and constructed wetlands, as well as optimal combinations of BMPs for removing contaminants found in poultry litter. Modifications to poultry feed to reduce phosphorus in litter and similar research should be explored as well. See the research needs in Section 3.G, BMPs to address animal waste, on page 56.

- ***Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.*** Recommended research includes the effectiveness of biodrying as a waste management practice, research on waste storage in earthen confinements or lagoons, and research on the benefits of composting as an alternative to lagoon storage prior to spreading on fields. See the research needs discussion under BMPs to address animal waste, on page 56 under research needs.

  Research on effectively treating animal wastes is important because of the high potential for feeding operations to contribute contaminants with acute and serious health effects—such as pathogens, nitrates, antibiotics, pesticides, and hormones—to both ground water and surface water. Animal feeding operations have been a major focus of efforts under CWA programs, which would benefit from reduction of wastes. Given the prevalence of animal feeding operations, adoption and effective implementation of BMPs can have a widespread, positive effect.

Three national priority research needs related to management measures to address fertilizers, pesticides, and herbicides include:

- ***Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips.*** The scientific literature contains a great deal of research related to BMPs addressing fertilizer. Additional research is needed on the effectiveness of specific BMPs, such as crop rotation and filter strips, and on nutrient removal on a regional scale in various areas of the country. See the discussions of research needs related to BMPs to address fertilizer application on page 58 under research needs.

- ***Precision agriculture technologies, especially the development of low-cost techniques for fertilizers.*** In addition to a better understanding of which BMPs are useful in various regions of the country (described above), research is also needed on *specific* technologies and practices. Precision farming involves the use of technologies such as soil sampling, remote sensing, geographic information systems (GIS), and the Global Positioning System (GPS) to evaluate field conditions and precisely adjust the amounts of fertilizer and application rates. This relatively new concept is promising, and additional research into the effectiveness and profitability of precision methods is a research priority. See more on the use of precision farming to address fertilizer application on page 58 under research needs.

- ***Crop management methods to minimize both fertilizer and pesticide/herbicide needs and releases to runoff.*** While progress has been made in reducing the need for fertilizers and increasing the efficiency of their application, research gaps remain. More research is needed on the effectiveness of specific BMPs, such as crop rotation and filter strips to reduce pesticide, herbicide, and fertilizer pollution, and on nutrient removal technologies. For more on research needs related to the use of these methods to address fertilizer application, see page 58; for more on research needs related to pesticides and herbicides, see the discussion of research needs on page 62.

  Research to address the use of fertilizers, pesticides, and herbicides in agricultural settings is considered a national priority because contaminants in these products (e.g., pathogens and nitrates) can have acute health effects, and pesticides and herbicides are expensive to remove from drinking water sources. If the billions of acres of farmland in the U.S. are properly managed, fertilizer, pesticide, and herbicide use can be reduced. Further, a greater understanding of which BMPs work best and most cost-effectively under various conditions will increase their acceptance and use.

Effective Contingency Planning

- ***Real-time or near real-time pathogen and virus detection.*** Potential technologies, on-line systems, and laboratory or field instruments to detect existing and emerging pathogens, viruses, and bioterrorism agents to be explored include continuous adenosine triphosphate analyzer, immunomagnetic separation, Microtox system, polymerase chain reaction-yielding DNA analysis, flow cytometry, and fish- and daphnid-based real-time toxicity sensors. See more on pathogen detection research on page 78 under research needs.

- ***Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants.*** For chemical and radiological contaminants, promising detection technologies include remote sensing, combined (bio)sensors and analytical techniques such as capillary electrophoresis-immunoassays, fiber optics with molecular imprinting, and genetically engineered microorganisms. Continued research to fully develop these methods as reliable for rapid detection, especially for drinking water systems, is needed. (See page 79 for further discussion of these methods.)

- ***Testing and application of early warning chemical monitoring technologies.*** Research should be directed towards testing and application of promising technologies, such as a microsensor monitoring system for volatile organic chemicals and other chemical sensors currently under development. Research should also focus on developing low-cost methods to screen for emerging contaminants of concern, such as pharmaceuticals, algal toxins, metabolites of pesticides, and viruses. See the discussion of research needs on detection methodologies on page 82 under research needs.

- ***Containment methods to address existing and emerging contamination threats.*** Given recent concerns about newly emerging contamination threats (e.g., bioterrorism agents) that could potentially affect the health of large numbers of people and for which treatment may be expensive or unavailable, water system operators and planners need to be able to react quickly to contain these substances when and if they are detected. The applicability of the containment methods such as those discussed in Section 4.B, beginning on page 83, to biological agents and pathogens may warrant further research.

The research on detection and early warning methodologies described above is considered a national priority because early warning of the presence of pathogens, existing and emerging contaminants, and bioterrorism agents can protect the health of large numbers of people. Further, the targets of these detection methodologies—organic compounds and microbials—currently require sophisticated expensive treatment. Containment methods would offer a last line of defense to protect intakes from contamination by these agents.

Social Science Research Need

There is one additional research need–on fertilizer use by and effectiveness of outreach programs to homeowners and non-agricultural users–that ranks high based on the scoring criteria. This research is usually done by researchers outside EPA; however it is presented here because of the high ranking. Research into the effectiveness of outreach materials for homeowners or owners/ operators of commercial spaces such as golf courses, retail establishments and office parks, cemeteries, and park lands is recommended. Also a better understanding of fertilizer and pesticide use in these applications is needed as well. See the discussions of research needs related to BMPs to address fertilizer application on page 58 under research needs.

As noted above, research to address the use of fertilizers is a national priority because contaminants in fertilizers, including nitrates can have acute health effects, especially to the very young. Public education or proper usage techniques for homeowners and other non-agricultural users can greatly reduce overall fertilizer use. The combined impact of millions of lawns throughout the nation has the potential for significant contamination, and many BMPs can be implemented at a relatively low cost.

See Appendix A for the Office of Water's Proposed Social Science Research Needs.

National SWP Research Priorities and EPA's Long-Term Research Plans

EPA is developing the Drinking Water Multi-Year Plan (MYP), which sets forth long-term research goals for the Office of Research and Development (ORD). Long-term goal #4 relates to protecting source waters and drinking water distribution systems, and OW has identified approximately 20 annual performance measures (APMs) related to SWP.

EPA is also developing a MYP for research on water quality standards (WQS), and has identified approximately 200 APMs related to its long-term research goals. Many of these relate to SWP, including research on indicators; BMPs for storm water, combined sewer overflows, and other contamination sources; setting TMDLs; and other topics.

There is some cross-over between the APMs identified in the MYPs and the priority SWP research needs. In particular, some APMs address at least a part of the priority research needed related to human health risk assessments for pathogens and algal toxins (1); refinement of indicator technologies (2); refining bacterial source tracking technologies (4); effectiveness of storm water BMPs in various situations or climates (5); optimal design and BMPs for septic systems in various climates and topography (6); alternatives to traditional septic systems (7); BMPs for controlling poultry wastes (8); real-time or near real-time pathogen and virus detection (13); promising technologies for detecting chemical and radiological contaminants (14); and testing and application of early warning chemical monitoring technologies (15). Exhibit 3 summarizes the cross-over.

Exhibit 3: Cross-Over Between Priority SWP Research Needs and Planned Long-Term Research

	Source Water Priority Research Need (From Table 1)	**Relevant APM(s)** [Relevant MYP]	**Lab ***
SETTING NATIONAL AND STATE STANDARDS			
1	Human health risk assessments for pathogens and algal toxins.	Report on the development of improved dose-response models for pathogens: *Cryptosporidium parvum* case study. [DW MYP]	NCEA
		Workshop and final report on the application of transmission models for use in pathogen risk assessment. [DW MYP]	NCEA
		Report on the potential health risks associated with three CCL pathogens [coxsackievirus, calicivirus, *Mycobacterium*].	NCEA
		Assessment of CCL pathogens. [DW MYP]	NCEA
		Characterization of human exposure to viruses from groundwater. [DW MYP]	NERL
2	Refinement of indicator technologies.	Report on faster, simpler indicator methods for fecal contamination. [WQS MYP]	NERL
		Evaluate the efficacy of AFLP technology as a fast and reproducible molecular tool to discriminate among species of enterococci. [WQS MYP]	NERL
		Application and evaluation of molecular methods (AFLP and others) to discriminate between human and non-human sources of fecal indicator bacteria. [WQS MYP]	NERL
		Evaluate the DNA-based technology in impaired watersheds impacted by fecal contamination from diverse sources under a range of temporal (different flow dynamics, after strong rain episodes) and spatial (distance from the source, water vs. sediment) variability. [WQS MYP]	NERL
		Data on drinking water pathogens using a proteomics based approach. [DW MYP]	NERL
		Data on the utility of chemical indicators of human fecal contamination and their correlation to health effects. [DW MYP]	NERL
SOURCE WATER ASSESSMENT PROCESS			
3	Robust and easy to use computer programs to support delineations.	None Specifically Identified.	
4	Refining bacterial source tracking technologies.	Report on the feasibility of applying DNA sequencing techniques in determining the animal source type of *Cryptosporidium* oocysts found in source water supplies. [DW MYP]	NRMRL

Exhibit 3: Cross-Over Between Priority SWP Research Needs and Planned Long-Term Research

	Source Water Priority Research Need (From Table 1)	**Relevant APM(s)** [Relevant MYP]	**Lab ***
PREVENTIVE MEASURES AGAINST VARIOUS SOURCES OF CONTAMINATION			
5	Effectiveness of storm water BMPs in various situations or climates.	Evaluate the effectiveness of selected structural BMPs to help macro nutrient balances and sediments in source water turbidity, algae, taste and odor. [DW MYP]	NRMRL
		Methodology for evaluating the effectiveness of watershed scale non-point source control BMPs for atrazine. [DW MYP]	NRMRL
		Placement of BMPs for source water/sediment control to achieve watershed TMDL goals. [DW MYP]	NRMRL
		Report on modeling and placement of structural BMPs as a source water protection approach. [DW MYP]	NRMRL
		Update Storm Water Management Model for use by states, utilities and consulting firms in allocating pollutants in urban watersheds to meet TMDL requirements. [WQS MYP]	NRMRL
		Report demonstrating the application of stormwater structural BMP effectiveness and cost data to meet sediment TMDLs. [WQS MYP]	NRMRL
		Report on the capability of the updated Stormwater Management Model to predict drainage from alternative systems as a tool to assist in meeting TMDL requirements. [WQS MYP]	NRMRL
		Provide states a document on managing pathogen contamination in the urban watershed providing watershed managers information on health effects, detection methods and best management practices to meet TMDL requirements. [WQS MYP]	NRMRL
		Report on techniques to mitigate adverse and counter-intuitive water quality impacts associated with the selection and placement of BMPs in urban watersheds. [WQS MYP]	NRMRL
6	Optimal design and BMPs for septic systems in various climates and topography.	Report on the performance verification (summary of Environmental Technology Verifications) of on-site residential contaminant reduction/septic system technologies. [DW MYP]	NRMRL
		Report on of BMP's in mixed land-use watersheds to meet water quality goals. [WQS MYP]	NRMRL
		Report on modeling and placement of structural BMPs as a source water protection approach. [DW MYP]	NRMRL
7	Alternatives to traditional septic systems.	Water Environment Research Foundation's $5 million grant for septic system research. [WQS MYP]	NRMRL
		State-of-the-science report for on-site sewage management and septic systems technology. [DW MYP]	NRMRL
8	BMPs for controlling poultry wastes.	Conduct health benefit studies evaluating the reduction in exposure to microorganisms in bank filtration versus conventional treatment. [DW MYP]	NHEERL
		Develop a strategy to evaluate BMP performance via molecular based methods in watersheds impaired by fecal contamination. [WQS MYP]	NRMRL
		Report on BMP performance and cost data for controlling nutrients, clean sediments, pathogens, toxic chemicals (metals and PBTs) and flow variations within mixed landuse watersheds and identifies information/research gaps. [WQS MYP]	NRMRL
		Publish a report that quantifies the amount of key stressors (nutrients, pathogens, toxics and clean sediments) that can be	NRMRL

Exhibit 3: Cross-Over Between Priority SWP Research Needs and Planned Long-Term Research

	Source Water Priority Research Need (From Table 1)	**Relevant APM(s)** [Relevant MYP]	**Lab ***
		eliminated and/or reduced on a national scale through the control of major sources of the stressor, i.e., CAFOs, air deposition, wet weather flow. [WQS MYP]	
9	Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.	None Specifically Identified.	
10	Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips.	None Specifically Identified.	
11	Precision agriculture technologies, especially the development of low-cost techniques for fertilizers.	None Specifically Identified.	
12	Crop management methods to minimize both fertilizer and pesticide/herbicide needs and releases to runoff.	None Specifically Identified.	
EFFECTIVE CONTINGENCY PLANNING			
13	Real-time or near real-time pathogen and virus detection.	Biosensor evaluation and demonstration as a tool to protect source waters. [DW MYP]	NRMRL
		Data on the utility of chemical indicators of human fecal contamination and their correlation to health effects. [DW MYP]	NERL
		Develop neural network model for Kentucky River to indicate presence, concentration, age and source of microbial pathogens. [DW MYP]	NCER
		Report on molecular microarrays for detection of non-pathogenic bacteria and bacterial pathogens in drinking water source waters. [DW MYP]	NRMRL
		State-of-the-science report on real time early warning systems for source water protection. [DW MYP]	NRMRL
		Improved methods for drinking water microbes (Report on advances in protozoan detection procedures). [DW MYP]	NERL
		Improved methods for CCL-related microbes for use in the Unregulated Contaminant Monitoring Rule (UCMR) [e.g., enteroviruses, caliciviruses, rotaviruses]. [DW MYP]	NERL
14	Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants.	Improved method for CCL-related chmicals (e.g., NDMA) [DW MYP]	NERL
		Develop rapid micro- and macro- methods for screening large number of contaminants. [DW MYP]	NHEERL
		Improved method for rapid detection of water quality changes. [DW MYP]	NERL

Exhibit 3: Cross-Over Between Priority SWP Research Needs and Planned Long-Term Research

	Source Water Priority Research Need (From Table 1)	**Relevant APM(s)** [Relevant MYP]	**Lab** *
15	Testing and application of early warning chemical monitoring technologies.	Biosensor evaluation and demonstration as a tool to protect source waters. [DW MYP]	NRMRL
		Data on the utility of chemical indicators of human fecal contamination and their correlation to health effects. [DW MYP]	NERL
		Report on early warning upstream monitoring network to protect source waters. [DW MYP]	NRMRL
		Develop neural network model for Kentucky River to indicate presence, concentration, age and source of microbial pathogens. [DW MYP]	NCER
		Report on molecular microarrays for detection of non-pathogenic bacteria and bacterial pathogens in drinking water source waters. [DW MYP]	NRMRL
		State-of-the-science report on real time early warning systems for source water protection. [DW MYP]	NRMRL
		Improved methods for drinking water microbes (Report on advances in protozoan detection procedures). [DW MYP]	NERL
16	Containment methods to address existing and emerging contamination threats.	None Specifically Identified.	
* Key to lab abbreviations: NCER - National Environmental Research Laboratory; NERL - National Exposure Research Laboratory; NRMRL - National Risk Management Research Laboratory, NCEA - National Center for Environmental Research			

A number of gaps remain, however. They include the following:

Refinement of indicator technologies:

- Refinement and improvement of indicator technologies for detecting fecal contamination and other pathogens, including improving analytical methods, better source identification (animal vs. human), better indicators for pathogens, and methods for dealing with multiple stressors.

Refining bacterial source tracking technologies:

- Research focused on identifying the sources of fecal bacteria, and which methods are most suited for identifying various species (e.g., of livestock known to be present in source water areas).

- A "toolbox" of source tracking methodologies to help managers select technologies most appropriate to the specific situation.

Effectiveness of storm water BMPs in various situations or climates.

- It is unclear which BMPs will be evaluated in the MYP and their applicability to storm water. Fully characterizing the efficacy and appropriateness of all BMPs could potentially be the subject of many studies.

- Tools to help planners select the most appropriate BMPs for use in their situation.

Optimal design and BMPs for septic systems in various climates and topography.

- Which septic system BMPs are cost-effective to install and operate, especially in various climates or topography.

Real-time or near real-time pathogen and virus detection and testing and application of early warning monitoring technologies.

- It appears that the pathogen and chemical detection methodologies are a significant focus of the drinking water MYP. The results of the planned research may satisfy the research needs of the Source Water Protection program.

Methodology for Determining National Research Priorities

To identify which research needs are of the highest priority (see Table 1), each is rated against certain "priority setting" criteria. (See the next section on research needs and gaps by national program policy area for more on how these needs were identified.) The criteria were set up to call out research that offers the biggest "bang for the buck" in the shortest period of time for achieving policy objectives. Bias here is toward research applied to meet national objectives, as opposed to basic research that is typically conducted over the longer term. Both core "source water assessment and protection" criteria, plus an additional criterion of broader applicability to other programs are used to score and prioritize research needs. Using the following scoring system, the SWP core program and additional criteria were used to identify national research priorities:

Score	Definition
1	Applicable
2	Applicable, but not widespread
3	Applicable and widespread

1. *Does the research provide outstanding benefits to both CWA and SDWA goals?* Research that furthers the goals of one program or the other would rate a low score, while a medium score would be applied to research that supports both programs to some degree or benefits one program to a great degree and offers some benefit to the other. The highest scores would be given to research that would bolster the major goals of both programs, such as contributing to setting TMDLs or addressing nonpoint source pollution.

2. *Would the research benefit people and water systems using both ground water and surface water?* Research that focuses on either ground water or surface water with no applicability to the other source type would receive a low score. Research that applies to both ground water and surface water in some geologic or land use settings, or that is particularly applicable to one source type with a lesser applicability to the other would receive a medium score. High scores are applied to research that applies to watersheds and aquifers nationwide.

3. *Does the research have the potential to reduce costs to drinking water systems?* Research into methods or technologies that would prevent or mitigate the introduction of contaminants to source waters (especially those that require expensive, sophisticated treatment technologies to detect or remove) can reduce monitoring or treatment costs. Research that focuses specifically on treatment or monitoring with no applicability to the other would receive a low score, as would research that requires other factors to be in place or additional research to realize these benefits. Research that applies to contaminants, such as microorganisms and viruses and certain metals such as arsenic, that are expensive or difficult to both treat and detect would receive the highest score.

4. *Would the research significantly help to improve public health?* For example, (a) would it result in the widespread reduction of contaminants, (b) address the most pervasive contamination sources, or (c) benefit the health of large populations? The highest scores are applied to research that would promote all three benefits, and lower scores are given to research that promotes one or two of these benefits, or that requires other factors to be in place or additional research to realize public health benefits.

5. *Would the research reduce the threat of contaminants with acute harmful health effects from entering source water, and potentially benefit sensitive subpopulations?* Such research might address pathogens to reduce the incidence of waterborne disease outbreaks, nitrates that may affect the very young, or certain bioterrorism agents. In addition, some metals, such as cadmium or chromium, could, if ingested in high concentrations, could cause acute health effects. The highest scores are applied to research that would address the greatest number of contamination threats or benefit the most subpopulations.

6. *Does the research have broader application to other environmental programs?* Research that addresses or reduces releases of hazardous wastes or pesticides to benefit environmental initiatives beyond those of the Office of Water meets this criterion. While all research that protects drinking water sources is likely to offer ancillary benefits to other programs, research that is applicable to the most programs outside of the Office of Water would receive the highest scores.

Each research need identified in this paper (see Table 2) is evaluated against the above criteria, and given a score of 1 to 3, depending on the degree to which it satisfies the criterion, as described above. The scores are then added, and the research needs with the highest total scores are considered to be priority needs, because they demonstrate the greatest applicability to most or all of the priority setting criteria. Table 1 summarizes this ranking.

It should be noted that it is difficult to assign an absolute rank or determine how much more pressing the top needs are over other needs. The scores presented in Table 1 do not necessarily directly correlate to the magnitude of the specific research need (i.e., a need with a score of 10 is not necessarily twice as critical as one with a score of 5). A significant amount of judgment is applied in assigning a score to a research need based on the criteria, and reasonable people may disagree on those scores.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
SETTING NATIONAL AND STATE STANDARDS TO SUPPORT SWP								
Modeling exposure and occurrence of contaminants.	3	2	1	2	3	11	1	12
Human health risk assessments for pathogens and algal toxins.	3	1	1	3	3	11	2	13
Refinement of indicator technologies.	3	2	2	3	3	13	1	14
SOURCE WATER ASSESSMENT PROCESS								
Robust and easy to use computer programs to support delineations.	3	3	2	2	1	11	2	13
Application of various tracers in ground water source delineations.	1	1	2	1	1	6	2	8
Field studies of the infiltration properties of various sediment types.	1	1	1	1	1	5	2	7
Decision support tools for selecting surface water source delineation methods.	1	1	1	1	1	5	1	6
Expanded research on conjunctive delineation.	1	3	1	1	1	7	1	8
Support contamination source inventories by linking data bases and using GIS.	2	2	1	1	1	7	2	9

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
Refining bacterial source tracking technologies.	3	2	2	3	3	13	2	15
Comparing the accuracy and cost-effectiveness of susceptibility determination methods in use for drinking water sources.	2	2	1	1	1	7	1	8
Consistent methods for use in area-wide assessments of specific geologic and geographic settings.	2	2	1	1	1	7	1	8
Constructing confidence bounds for susceptibility determination results.	2	1	1	1	1	6	1	7
PREVENTIVE MEASURES AGAINST VARIOUS SOURCES OF CONTAMINATION								
BMP selection tools.	2	2	1	2	2	9	1	10
Performance of BMPs as installed.	2	2	1	1	1	7	1	8
Consistent methods for comparing and evaluating BMPs.	1	2	1	1	1	6	1	7
Optimal structures of watershed groups implementing prevention measures.	1	2	1	1	1	6	1	7
Effectiveness of storm water BMPs in various situations or climates.	3	3	2	2	2	12	2	14
Evaluation of low-cost storm water BMPs.	2	2	2	2	1	9	2	11
Improved oil-grit separators suitable for small impervious areas, e.g., parking lots.	2	2	2	2	1	9	1	10

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
Optimal design and BMPs for septic systems in various climates and topography.	3	3	2	3	3	14	1	15
Alternatives to traditional septic systems.	3	3	2	3	3	14	1	15
Presence and impacts of endocrine disruptors in septic system wastes.	2	2	2	2	1	9	1	10
ASTs that can withstand severe weather, earthquakes, and collisions.	1	1	1	1	1	5	2	7
Low-cost leak detection equipment for ASTs.	1	1	1	1	1	5	2	7
Reliable UST leak-detection technologies.	1	1	1	1	1	5	2	7
UST designs for earthquake-prone areas.	1	1	1	1	1	5	2	7
Studies of BMP effectiveness specific to vehicle wash wastes.	1	1	2	1	1	6	2	8
Expanded research on innovative technologies for Small Quantity Generators, e.g., wet-cleaning.	2	2	2	1	1	8	2	10
Low-cost BMP selection tools for Small Quantity Generators.	1	2	2	1	1	7	3	10
Ability of BMPs to remove hormones and antibiotics from animal wastes.	2	2	2	2	1	9	2	11
BMPs for controlling poultry wastes.	3	3	2	3	3	14	1	15

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.	3	2	2	3	3	13	1	14
Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips.	3	2	2	3	3	13	1	14
Precision agriculture technologies, especially the development of low-cost techniques for fertilizers.	3	2	2	3	2	12	2	14
Research on the effectiveness of BMPs for agricultural drainage wells.	2	1	1	1	2	7	2	9
Crop management methods to minimize both fertilizer and pesticide/herbicide needs and releases to runoff.	2	2	2	3	2	11	2	13
Fertilizer use by and effectiveness of outreach programs to homeowners and non-agricultural users.	2	2	2	3	3	12	2	14
Effectiveness of pesticide removal by constructed wetlands and grassed buffer areas.	2	2	2	2	1	9	3	12
Reducing pesticide and herbicide use by or proper techniques for homeowners and non-agricultural users.	2	2	2	3	1	10	1	11
Emerging technologies related to treating CSOs and SSOs.	3	1	1	2	2	9	1	10
Impacts of pharmaceuticals and other chemicals in biosolids.	3	1	2	2	1	9	1	10
Research on which biosolids measures are the most effective in various regions of the country.	3	1	2	2	3	11	1	12

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
Continued research on Class V injection wells.	2	1	1	3	3	10	2	12
Alternatives to discharging to floor drains.	2	1	2	1	1	7	2	9
Technical assistance on properly interpreting available geophysical data on abandoned wells.	1	1	1	1	1	5	1	6
Tools to link and display new and historical land use and contaminant source data for locating abandoned wells.	1	1	1	1	1	5	1	6
Linking conservation and reuse/recycling programs to water quality improvements.	1	2	2	1	1	7	1	8
Potential negative water quality impacts of reduced waste water flows.	2	1	2	1	1	7	1	8
Effective conservation methods for reducing water use and maintaining water quality for various land uses.	1	2	2	1	1	7	1	8
Research on how storage and recharge operations affect water quality.	1	2	1	1	1	6	1	7
Disinfection by-product formation in finished water reservoirs and aquifers.	1	2	1	2	1	7	1	8

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Table 1: Identifying Priorities for Source Water Assessment and Protection Research								
Research Needs (from Table 2)	1. CWA and SDWA benefits	2. Ground & surface water	3. Reduce costs	4. Improve public health	5. Acute health benefits	Core SWP Score Σ1 - 5	6. Broader applicability	Combined Overall score Σ1 - 6
EFFECTIVE CONTINGENCY PLANNING								
Real-time or near real-time pathogen and virus detection.	3	2	3	3	3	14	2	16
Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants.	2	1	3	3	2	11	2	13
Time of travel to surface water intakes.	3	1	3	2	2	11	1	12
Testing and application of early warning chemical monitoring technologies.	2	2	3	3	3	13	2	15
Containment methods to address existing and emerging contamination threats.	2	1	3	3	2	11	2	13
Readiness to respond to the most-probable threats within a given water supply area.	2	1	2	2	2	9	1	10

Description of scores: 1= applicable to only certain aspects of criterion or would require additional research to benefit criterion; 2 = applicable but not widespread contribution to meeting all components of the criterion, or extensive contribution to certain aspects of the criterion; 3 = applicable and widespread contribution to satisfying all aspects of the criterion. The top research needs are shaded.

Overall Research Needs by National Program Policy Area

A number of priorities for research must be met to improve the body of knowledge on each of the specific research topics outlined in this paper. To identify research needs within each source water assessment and protection program policy area, two criteria were applied:

- *Does the research need address key research questions?* The research questions presented throughout this report define the scientific needs to adequately plan and manage source water assessment and protection programs.
- *Is the research not currently being performed?* The needs identified are "gaps" between completed or ongoing research and the information needed to more effectively answer the research question.

Table 2, on the following pages, summarizes key research questions and research needs that meet the above criteria. The body of this report describes these research topics and needs in greater detail. Research needs for each research topic are also highlighted in boxes at the front of each section and described in detail in subsections titled "Research Needs." Also included in the body of the report are other identified research gaps that do not necessarily answer the above questions (and therefore are not considered the top needs for each topic), but are worthy of note in this research paper.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
SETTING NATIONAL AND STATE STANDARDS TO SUPPORT SWP		
Water Quality Standards	Which planned CWA research efforts can also benefit drinking water protection goals?	✓ Modeling exposure and occurrence of contaminants. ✓ Human health risk assessments for pathogens and algal toxins. ✓ Refinement of indicator technologies.
SOURCE WATER ASSESSMENT PROCESS		
Ground Water and Surface Water Delineation	What cost-effective delineation techniques can provide an effective and defensible description of a well or wellfield recharge area? What are the most useful ways to identify critical areas in watersheds to ensure that the most effective priorities for prevention and contingency planning actions are implemented efficiently? What criteria should be used to compare available delineation techniques?	✓ Robust and easy to use computer programs to support delineations. ✓ Application of various tracers in ground water source delineations. ✓ Field studies of the infiltration properties of various sediment types. ✓ Decision support tools for selecting surface water source delineation methods. ✓ Expanded research on conjunctive delineation.
Inventories of Potential and Actual Contaminant Sources	What is the most efficient way to link disparate existing data on regulated point sources of contamination? What cost-effective technologies can be used for an accurate and defensible listing and display of actual and potential sources of contamination?	✓ Support contamination source inventories by linking data bases and using GIS. ✓ Refining bacterial source tracking technologies.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
Susceptibility Determinations	What are the most cost-effective and accurate methods to identify actual current sources of contamination of source waters? What is the most accurate method to describe the relative threats from different sources of contamination to a public water supply? What is the most accurate method to describe the relative threats from various sources of contamination to multiple PWS resource-wide areas? What is the most accurate method to rate and rank PWSs against each other on a susceptibility scale?	✓ Comparing the accuracy and cost-effectiveness of susceptibility determination methods in use for drinking water sources. ✓ Consistent methods for use in area-wide assessments of specific geologic and geographic settings. ✓ Constructing confidence bounds for susceptibility determination results.
PREVENTIVE MEASURES AGAINST VARIOUS SOURCES OF CONTAMINATION		
Preventive Measures Against Various Sources of Contamination	For all sources, what criteria should be used to determine the effectiveness of BMPs?	✓ BMP selection tools. ✓ Performance of BMPs as installed. ✓ Consistent methods for comparing and evaluating BMPs.
Watershed Organizational Alternatives	What is the best way to organize localities to get the maximum prevention for key threats?	✓ Optimal structures of watershed groups implementing prevention measures.
BMPs for Storm Water Runoff	What are the cost and performance considerations for storm water BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Effectiveness of storm water BMPs in various situations or climates. ✓ Evaluation of low-cost storm water BMPs. ✓ Improved oil-grit separators suitable for small impervious areas, e.g., parking lots.
BMPs for Septic Systems	What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters from septic systems?	✓ Optimal design and BMPs for septic systems in various climates and topography. ✓ Alternatives to traditional septic systems. ✓ Presence and impacts of endocrine disruptors in septic system wastes.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
BMPs for Above-Ground Storage Tanks (ASTs)	What are the cost and performance considerations for BMPs for above-ground storage tanks to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ ASTs that can withstand severe weather, earthquakes, and collisions. ✓ Low-cost leak-detection equipment for ASTs.
BMPs for Underground Storage Tanks (USTs)	What are the cost and performance considerations for BMPs for underground storage tanks to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Reliable UST leak-detection technologies. ✓ UST designs for earthquake-prone areas.
BMPs for Vehicle Washing Facility Wastes	What are the cost and performance considerations for BMPs for vehicle washing facilities to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Studies of BMP effectiveness specific to vehicle wash wastes.
BMPs for Small Quantity Chemical Use, Storage, and Disposal	What are the cost and performance considerations for BMPs that could be implemented at facilities that use, store, and dispose of small quantities of chemicals in order to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Expanded research on innovative technologies for Small Quantity Generators, e.g., wet-cleaning. ✓ Low-cost BMP selection tools for Small Quantity Generators.
BMPs for Animal Waste	What are the cost and performance considerations for BMPs for animal feeding operations to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Ability of BMPs to remove hormones and antibiotics from animal wastes. ✓ BMPs for controlling poultry wastes. ✓ Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
BMPs for Fertilizer Application	What are the cost and performance considerations for BMPs to prevent or minimize discharges of fertilizers, or minimize the geographic spread of fertilizers to source waters?	✓ Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips. ✓ Precision agriculture technologies, especially the development of low-cost techniques. ✓ Research on the effectiveness of BMPs for agricultural drainage wells. ✓ Crop management methods to minimize both fertilizer and pesticide/herbicide needs and releases to runoff. ✓ Fertilizer use by and effectiveness of outreach programs to homeowners and non-agricultural users.
BMPs for Pesticide and Herbicide Use	What are the cost and performance considerations for BMPs to prevent or minimize discharges of pesticides and herbicides, or minimize the geographic spread of pesticides and herbicides to source waters?	✓ Effectiveness of pesticide removal by constructed wetlands and grassed buffer areas. ✓ Crop management methods to minimize both pesticide/herbicide and fertilizer needs and release to runoff. ✓ Reducing pesticide and herbicide use by or proper techniques for homeowners and non-agricultural users.
BMPs for Combined and Sanitary Sewer Overflows	What are the cost and performance considerations for BMPs for combined and sanitary sewer overflows to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?	✓ Emerging technologies related to treating Combined Sewer Overflows (CSOs) and Sanitary Sewer Overflows (SSOs).
BMPs for Biosolids Application	What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters due to biosolids application?	✓ Impacts of pharmaceuticals and other chemicals in biosolids. ✓ Research on which biosolids measures are the most effective in various regions of the country.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
BMPs for Injection Wells	What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters due to injection wells?	✓ Continued research on Class V injection wells. ✓ Alternatives to discharging to floor drains.
BMPs for Abandoned Wells	What are the cost and performance considerations for methods to prevent contamination of source water due to the presence of abandoned wells in water supply areas?	✓ Technical assistance on properly interpreting available geophysical data on abandoned wells. ✓ Tools to link and display new and historical land use and contaminant source data for locating abandoned wells.
BMPs Involving Water Conservation, Reuse, and Recycling	How can water conservation, reuse, and recycling minimize contamination or the geographic spread of contaminants to source waters?	✓ Linking conservation and reuse/recycling programs to water quality improvements. ✓ Potential negative water quality impacts of reduced waste water flows. ✓ Effective conservation methods for reducing water use and maintaining water quality for various land uses.
BMPs Involving Aquifer Recharge, Storage and Recovery, and Remediation	How can aquifer recharge, aquifer storage and recovery, and aquifer remediation minimize contamination or the geographic spread of contaminants to source waters?	✓ Research on how storage and recharge operations affect water quality. ✓ Disinfection by-product formation in finished water reservoirs and aquifers.

Table 2: Key Research Questions and Research Needs for Source Water Assessment and Protection		
Research Topic	**Key Research Questions**	**Research Needs**
EFFECTIVE CONTINGENCY PLANNING		
Detection Methodologies	What are the most efficient and effective methods for monitoring for various contaminants introduced accidentally or deliberately to source waters?	✓ Real-time or near real-time pathogen and virus detection. ✓ Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants. ✓ Time of travel to surface water intakes. ✓ Testing and application of early warning chemical monitoring technologies.
Response Systems	What are the most efficient and effective methods for containing accidental or deliberate emergency situations in ground water and surface water supplies?	✓ Containment methods to address existing and emerging contamination threats. ✓ Readiness to respond to the most-probable threats within a given water supply area.

Organization of this Report

Identifying and prioritizing research needs is necessary to guide decision-makers in developing and implementing effective protection programs and to make the most of limited resources. Key research questions are presented for each topic area in this report.

To answer these questions, a state of the science overview of what has happened in the last two decades is presented, along with a description of relevant ongoing research initiatives. Based on this, the report identifies gaps in the body of available research. Those research needs that answer the three research questions identified on page xxvi are highlighted under "Research Needs" in each section (they are also highlighted at the front of each section and in Table 2). Other research gaps that do not directly answer the above questions (and are thus not considered to be top research needs), but are worthy of note in this research paper, are presented as well.

To identify national priorities for source water assessment and protection research that span the range of research topics, EPA applied the six criteria described on page xvii to each identified research need by topic area. Those research needs that correlate the strongest to the research criteria (as described in the introduction to Table 1) are considered priority research needs. These are highlighted under "National Research Priorities," beginning on page iv.

The body of this report is organized according to national program policy areas. Research activities and gaps in the following areas are described: water quality standards setting (Section 1); the source water assessment process, including delineations, contaminant source inventories, and susceptibility determinations (Section 2); preventive measures to address sources of contamination, such as BMPs and conservation measures (Section 3); and contingency planning, including detection and response methodologies (Section 4).

An extensive bibliography of research on the topics addressed in this research paper is presented in Appendix B.

1. Setting National and State Standards to Support SWP

Research Question

Which planned CWA research efforts can also benefit drinking water protection goals?

> ***Research Needs...***
>
> - ✔ Modeling exposure and occurrence of contaminants.
> - ✔ Human health risk assessments for pathogens and algal toxins.
> - ✔ Refinement of indicator technologies.

State of the Science

Under the Clean Water Act (CWA), states and authorized tribes must adopt water quality standards (WQS) to protect navigable waters of the United States. Most states developed WQS and criteria in the 1970s, and standards and criteria were rarely fine-tuned to address complex issues such as protecting endangered or threatened species, assessing sedimentation and flow, or evaluating ecosystem-wide effects from combinations of pollutants or stressors (EPA, 2002).

Evolving science, increasing implementation demands, and other circumstances such as a focus on TMDLs, nonpoint source pollution, rapid population growth, and storm water issues, have often significantly outpaced efforts by EPA and the states to update WQS.

Ongoing Research

The Office of Water (OW) and the Office of Research and Development (ORD) are preparing the Strategic Planning and Research Coordination (SPRC) document, which establishes goals and strategic research directions. Nine OW priority science needs were highlighted and were the focus of breakout groups, which have prepared preliminary reports of research needs, several of which are applicable to source water assessment and protection:

Modeling research needs identified focus on Total Maximum Daily Loads (TMDLs). Short-term goals for TMDL research include methods to interpret narrative criteria and improved input data for loading and ambient characterization. Research topics include sampling methods for pathogen modeling; development of the FARM manual to evaluate effectiveness of BMPs; and nutrients. Long-term activities include developing methods to identify and address the specific pollutant causing an impairment; and increasing the rigor and accuracy of models to improve the overall quality and defensibility of TMDLs. Long-term research goals include better source identification (animal vs. human) and better indicators for pathogens and methods for dealing with multiple stressors.

Other modeling needs not directly related to TMDL development include models to reflect surface water-ground water interaction or to estimate pesticide loadings and emerging contaminants, and methods to identify threatened water bodies to assess preservation/restoration options.

Nutrient Pollution research is aimed at producing tools to help evaluate and manage the risks to all water bodies posed by nutrient inputs. Priority research needs include total nutrient loading-ecological response relationships to support understanding of the impact of nutrient pollution, and nutrient fate and transport in surface and ground water. Also, research into identifying cost-effective nutrient management and risk reduction options available to reduce nutrient pollution problems is a priority. (See more on nutrient research under watershed management below.)

Microbial and Pathogen Contamination research needs focus on ambient, recreational, and drinking water for both human and ecosystem health. Research on waterborne pathogens is needed to address four objectives and several more sub-objectives for water resource managers. Preliminary high priority research needs have been identified; those related to source water are shown below.

Use technically sound criteria and risk assessments to protect human health and ecosystems from microbial contamination.

To provide sound data and analyses to assess risk for drinking water sources, the following priority research need is identified:

- Determine relationships for indicator levels and acceptable drinking water risks to establish source criteria.

To give managers sound data and analyses to characterize sources of animal borne human pathogens and assess human risk, the following are priority research needs:

- Determine the survivability of pathogens from animal operations in waste and runoff.
- Determine the effectiveness of current waste disposal and treatment methods for reduction of human pathogens.
- Determine or model the risks of human infection from animal waste sources, including increased risk due to proximity of the waste source.

Priority research for assessing risk from algal toxins includes:

- Conduct epidemiological and epizootiological studies to assess exposure to and acute and chronic effects of algal toxins on public health, terrestrial and aquatic animals.
- Determine the parameters which are likely to result in low level chronic occurrence of harmful algal species in water environments.
- Develop improved detection methods for known toxic algal species.

Use monitoring tools and diagnostic techniques to rapidly and/or accurately measure pathogens in different media and determine the potential causes and/or sources of pathogen contamination.

To improve analytical methods for indicators and specific pathogens, the following research needs were identified:

- Develop standardized extraction, detection, and quantification protocols for algal toxins and toxin metabolites.
- Develop and field-test a rapid, simple, inexpensive analytical method for screening of target algal toxins other than microcystins in ambient waters.
- Improved monitoring techniques for biosolids, including real-time monitoring of pathogens.
- Refine/develop/validate analytical methods with necessary precision and accuracy to detect and quantify fecal or "class" indicators, as well as fecal source indicators.

To improve monitoring protocols for different water body types, OW and ORD identified the following research priorities:

- Develop monitoring designs and protocols to determine the distribution and abundance of specific toxic algal species.
- Develop monitoring designs and protocols to detect bloom initiation and development based on environmental and/or ecological indicators.
- Develop reliable and rapid chemical or other non-mouse bioassays for algal toxins for field monitoring.
- Develop and test early warning indicator or method to predict the occurrence of toxic waterborne blooms.

Use modeling tools to forecast the impacts of mitigating pathogens through alternative protection and restoration strategies.

The following research would support routine estimations of point source and non-point source loadings of pathogens from multiple sources and pathways.

- Develop early warning systems for various problems areas, including drinking water sources, by integrating models with real-time monitoring data.

Protect and restore water bodies from microbial contamination by using cost-effective and readily applicable techniques.

To evaluate the efficacy of current technologies and newly developed technologies for mitigating pathogen risks from point source and non-point source discharges, the following research is needed:

- Determine the national rate and causes of septic tank failure and characterize the potential water quality and public health impacts.
- Characterize pathogen infectivity, density and survival from contaminant sources using various risk management practices.
- Develop and evaluate improved BMPs for minimizing pathogen risks from combined sewer overflows, sanitary sewer overflows, concentrated animal feeding operations, and failed sewer systems.
- Determine more effective means of animal waste disposal and treatments resulting in lowered pathogen occurrence.

Ecological Assessments and Restoration research needs include developing diagnostic indicators that establish scientifically defensible relationships between biological, chemical, and physical indicators of condition, stressors and effects.

Watershed Management research opportunities include developing watershed management tools to prevent, reduce or remove conventional pollutants from causing impairment. Selected research needs related to nutrient management, flow, and other watershed management needs are listed below.

Nutrient Management Research

The following research is needed to meet the present and future challenges to managing anthropogenic nutrient loads, including determining which nutrient(s) to control and identifying and prioritizing natural and anthropogenic sources, needs should be addressed:

- Quantify and/or compile information on the relative contribution of point, non-point and diffuse nutrient sources.
- Quantify and/or compile information on nutrient removals from existing and innovative structural and nonstructural nutrient source controls.
- Investigate watershed and receiving water characteristics that influence susceptibility to nutrient-overenrichment and/or toxicity, and the transferability of findings between studies.

Flow Related Research

- Determine when and how different pollutants enter the hydrologic cycle.
- Determine how pollutants migrate through the watershed in response to different flow regimes.
- Construct field scale pollutant transport models.

Other Watershed Management Research

- Development of cumulative effects methodologies to measure watershed-level impacts of stressors and/or management actions.
- Research into the nutrient removal effectiveness and optimal size of various BMPs, such as constructed wetlands and buffer zones.
- Development of low-cost alternatives to waste lagoons for treating runoff and solids collected from concentrated animal feeding operations.
- Continued advances in watershed-based modeling.

Research Needs

ORD has identified research needs and priorities related to setting WQS under the CWA, and those needs that have the greatest implications for drinking water source protection are highlighted above. Of the most pressing interest and benefit to source water assessment and protection are those research activities that would improve the science needed to set standards under the CWA for drinking water contaminants in ambient waters. Research into **modeling the occurrence of and human exposure to various contaminants** such as pathogens and nutrients would further this goal. Of particular note is planned research to improve TMDL setting, and assess risk from algal toxins, such as studies to assess exposure to, and acute and chronic effects of, algal toxins and nutrient fate and transport in surface and ground water. Similarly, research on **risk to humans from various contaminants** would be useful. Notable planned research includes research examining risk assessments to protect human health and ecosystems from pathogens and algal toxins.

Another research need is the **refinement and improvement of indicator technologies** for detecting fecal contamination and other pathogens. Pathogens such as *E. coli* are of special concern because of their acute health effects, particularly on sensitive subpopulations such as the elderly, children, or immuno-compromised individuals. Indicator technologies offer many potential benefits to source water assessment and protection. Accurate source inventories and susceptibility determinations hinge on an understanding of the location and number of contamination sources in both ground water- and surface water-based drinking water supply areas. (See Section 4.A on page 81 for a discussion of applications of indicator technologies to ground water sources.) These indicator technologies can also be used to link potential threats to actual contamination and support TMDL development and other management measures. As the numbers of land use activities potentially contributing to pathogens increases (e.g., farming and animal rearing practices, septic systems, and the use of fertilizers on home lawns), so does the importance of detecting pathogen contamination early.

2. Source Water Assessment Process

Source water assessments consist of three basic steps: delineation of the source water area–the ground water or surface water that supplies a water system, identification of actual and potential sources of contamination that could threaten a water supply, and a determination of the susceptibility of the water supply to identified threats.

2.A. Delineation of Source Water Areas

As the first step of the source water assessment process, the contributing areas to a ground water well or surface water intake must be delineated. For ground water, the area is defined by the portion of the land surface or aquifer that is hydraulically connected to the well within a specified distance or time of travel. Unconfined aquifers are in direct hydraulic connection with the surface and are generally more vulnerable than confined aquifers to contaminants originating at or near the land surface. Confined aquifers are found below less permeable or impermeable materials and are generally less vulnerable to contaminants from the land surface immediately around the drinking water well. For surface water, the source water area is defined by the watershed draining through the stream or lake that serves as the source of raw drinking water.

Research Questions

What cost-effective delineation techniques can provide an effective and defensible description of a well or wellfield recharge area?

What are the most useful ways to identify critical areas in watersheds to ensure that the most effective priorities for prevention and contingency planning actions are implemented efficiently?

What criteria should be used to compare available delineation techniques?

Research Needs...

- ✔ Robust and easy to use computer programs to support delineations.
- ✔ Application of various tracers in ground water source delineations.
- ✔ Field studies of the infiltration properties of various sediment types.
- ✔ Decision support tools for selecting surface water source delineation methods.
- ✔ Expanded research on conjunctive delineation.

The state of the science, ongoing research, and research needs related to ground water and surface water delineation methodologies are discussed below. Ground water/surface water interactions also have important implications for source water delineations; these are described in the discussion of susceptibility determinations in Section 2.C. Information gathered in the delineation process and the results of susceptibility determinations are closely linked and can affect each other; and managers should periodically revisit both processes.

State of the Science

Ground Water

Source water protection areas for ground water supplies must account for basic information on hydrogeology, ground water flow, water pumping rate, and delineation criteria. These protection areas are also referred to as "wellhead protection areas" (WHPAs), as introduced by the 1986 Safe Drinking Water Act (SDWA) amendments.

A variety of techniques exist for delineating WHPAs. These techniques (ranging from the simplest to the most complex) include: arbitrary fixed radii, calculated fixed radii, simplified variable shapes, analytical methods, hydrogeologic mapping, and numerical modeling. To guide decision-makers in the wellhead protection process, EPA and the states have developed tools and guidelines for delineating WHPAs.

Over the past 15 years, EPA and others (notably, the U.S. Geological Survey or USGS) have created a variety of computer models and codes for use in delineating WHPAs. The WHPA code is a semi-analytical ground water flow model, with particle tracking, developed by the EPA to assist in delineating capture zones of water supply wells in well head protection area studies.

One model of particular note is EPA's recently-developed Wellhead Analytic Element Model (WhAEM2000) to support the delineation of source water protection areas for ground water-based drinking water systems. WhAEM2000 is a public domain, ground water flow model that delineates protection areas based on various methods (e.g., fixed radius and uniform flow solutions). The program can account for influences on the ground water system such as pumping wells, rivers, recharge, and no-flow boundaries (Kraemer et al., 2000). Continuous enhancements to these models are being made to produce more accurate estimations of the flow patterns in various geologic settings.

Other examples of models include MODFLOW, currently the most widely used numerical model for ground water flow, and V2DSI, a model that simulates water flow and solute transport in variably saturated porous media. For example, several studies conducted through the USGS National Research Program (NRP) developed or tested models used to determine hydraulic properties and aquifer response to variations in recharge, stream-stage, and/or drawdown for confined and unconfined aquifers. One NRP study involved the development of a model that was used to analyze two alluvial stream-aquifers (Barlow et al., 2000; Moench et al., 2001). Another study revised an existing ground water flow model to better represent conditions in a coastal aquifer plain system in Virginia (McFarland, 1998). USGS has also studied ground water flow and transport through the use of particle tracking, concentration data, and graphical and numerical analysis. One such study addressed the development of the Advective-Transport Observation (ADV) Package as an addition to MODFLOW, and used it to test hypothesized recharge areas (Anderman and Hill, 2000). The Water Environment Research Foundation (WERF) compiled a review of currently available models and assessed their capabilities and limitations (WERF, 1999).

Other research has focused on analyzing the accuracy of flow models. The U.S. Department of Agriculture (USDA) and USGS have funded studies of source area delineation accuracy and uncertainty in determining aquifer properties. These studies compare models, present the benefits and limitations of different approaches, and add data to existing models to improve accuracy. For example, one study compared two models used to delineate WHPAs and evaluated the relative importance of various sources of uncertainty (Forster et al., 1997). The USGS also compiled a report on the state of the science for estimating recharge areas to wells that reviews concepts, assumptions, and uncertainties associated with modeling ground water flow (Franke et al., 1998).

Apart from EPA's effort, many ground water flow models (e.g., MODFLOW by the USGS) are available in the public domain and from the private sector. In general, the accuracy of the model results is proportional to the resources and data needed for the model.

Fractured Bedrock

Predicting flow through fractured bedrock is a major challenge to the science of hydrogeology. The zones of deep lineaments and large fractures in bedrock are associated with high hydraulic conductivity and high ground water flow rate. Unless the patterns of lineaments and fractures are accurately characterized, it would be very difficult to determine the origin of water from a fractured bedrock well. Fracture trace analysis (i.e., a geophysical method) and field exploration programs are typically used to confirm the locations and density of fractures.

Recent research has focused on characterizing fractured-rock aquifers using a combination of data (i.e., RADAR, tracer, and hydraulic data). Some of these studies have been conducted at the USGS Toxics Hydrology Program fractured-rock hydrology research site at Mirror Lake in New Hampshire (Day-Lewis et al., 2001; Tiedeman and Hsieh, 1999). Other studies include tracer and open-hole tests, conducted to determine ground water flow through fractured rock.

Karst Aquifers

Predicting flow through calcareous rocks (e.g., limestone) is another major challenge to the science of hydrogeology. The development of caverns and solution channels in limestone and dolomite results in multi-porosity that makes flow prediction a very difficult task. In general, the characterization of ground water flow in karst areas is conducted at a local level that is highly dependent on the network structure of the caverns and channels within the aquifer. Dye tracer tests have been considered the most successful methods for determining ground water flow in karst aquifers.

Many studies have presented techniques and theories for conducting dye tracer tests. A summary of dye tracing techniques and recent research was published by EPA (Mull et al., 1988). EPA developed the QTRACER program to facilitate evaluating tracer-breakthrough curves generated from tracing studies conducted in karst and fractured-rock aquifers. The results may then be applied in solute-transport modeling and risk assessment studies (EPA, 1998). In more recent years, research has focused on developing techniques such as age dating of water to determine residence time and source area for karstic aquifers. One study presented the advantages and disadvantages of several quantitative techniques for modeling of flow through karstic aquifers (Taylor and Greene, 2001). Additionally, the USGS Karst Interest Group was formed in 2000 to foster technology transfer and cooperative research in karst areas.

Surface Water

In general, due to other research objectives, methods for delineating watersheds and drainage basins are well established. Research over the past decades in fluvial geomorphology, hydrology, forestry, water quality analysis, and watershed management has sparked the development of a number of methodologies to delineate watersheds and drainage basins. As with ground water delineations, surface water body delineations can range from simple to complex, and some of these methods are more accurate and more costly to implement than others.

Among the more simplistic approaches are fixed distance/radii upstream of an intake or buffer zones of a specified width along the banks of a river, lake, or reservoir. These are relatively easy to implement using maps. The distance/radii and width of a buffer may vary based on flow rates, topography, or land uses in the area, if supporting information exists. Very limited work has been done to determine the optimal size of buffers necessary to protect drinking water intakes. A quick review of the water quality literature reveals a large number of studies on the impact of buffer zones on water quality (e.g., nutrient and sediment). However, very little of this research is tied directly to drinking water intakes.

For those water systems that withdraw water from major rivers or have large watersheds, it has been recognized that a "segmentation" approach is needed to better account for those areas that are more likely to directly affect the drinking water supply. Many states have adopted the use of buffers or setbacks around water intakes and along the rivers upstream to segment their large watersheds. For example, segmentation is a major step in EPA's Hydrologic Simulation Program-Fortran (HSPF) modeling program. This program has been used in watershed management studies across the U.S. (Chew et al., 1991; Donigian et al., 1996; Scheckenberger and Kennedy, 1994).

Many states are using time of travel to segment large watersheds to better account for those areas that are likely to quickly affect drinking water supplies. In addition, the time of travel criteria can be used to determine the vulnerability of the watershed, and prioritize assessment and protection activities (see Section 2.C). USGS has compiled a CD-ROM with time of travel calculations for average condition scenarios of streams as an information resource for selected large water systems that are conducting source water assessments (Alexander et al., 1999).

Conjunctive delineation is the integrated delineation of the zone of ground water contribution and the area of surface water contribution to a public water supply that withdraws ground water under the direct influence (GWUDI) of surface water. Studies on conjunctive delineation for areas with significant surface and ground water interactions are very limited.

More recently, with the advance of geographic information systems (GIS) and availability of digital elevation data (e.g., digital elevation model or DEM), automated methods have been developed to make the delineation of watersheds a less time-consuming task (Garbrecht et al., 2001; Schnabel and Day, 1998).

The Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system, developed by EPA's Office of Science and Technology, supports watershed and water quality-based assessment and integrated analysis of point and nonpoint sources. BASINS integrates a GIS, national watershed and meteorologic data, and state-of-the-art environmental assessment and modeling tools. The latest version of BASINS has the capability to conduct automated watershed delineation using DEMs.

Ongoing Research

Ground Water

On ground water flow, USGS's NRP is funding two programs focused on improving the effectiveness of ground water flow models. The first focuses on improving the characterization of complex aquifers with analytical models. The second program is focusing on improving mathematical models by developing equations to better describe ground water flow, identifying uncertainties in models, and deriving methods to assess the predictive quality of the models.

Ongoing research related to fractured bedrock is being conducted by the USGS Bedrock Regional Aquifer Systematics Study (BRASS). BRASS is developing cooperative research efforts to better understand ground water flow, availability, and quality in regions underlain by fractured bedrock. Current BRASS activities include hydrologic training, workshops, and fieldwork in Connecticut, New Hampshire, South Dakota, Pennsylvania, and Maryland. In addition, two National Research Program studies on the hydrology of fractured rocks, and transport in fractured rock are focused on developing theoretical and mathematical transport models.

Ongoing research on karst aquifers is being conducted in Michigan as part of the state's SWAP. The USGS and National Park Service are working cooperatively to create a National Atlas Karst Map, which will contain national data on karstic aquifers. A new scientific organization, the Hydrogeology Consortium, is also actively working on improving karst characterization through information sharing and cooperation between agencies and scientists.

Surface Water

Ongoing research on surface water delineations reflects states' efforts to conduct surface water characterization using various techniques. A USGS study is working to delineate watersheds utilizing a relatively simple program, the GIS Weasel, requiring only a digital elevation model and ancillary digital information. The GIS Weasel program is designed for users with no previous GIS experience. Another USGS study is using segmentation, as a part of the HSPF program, to better model the Potomac River watershed. The New Hampshire and Vermont Departments of Environmental Services and the USGS are conducting time of travel assessments for 13 river reaches in order to delineate six-hour contaminant reaches to a water intake or withdrawal point.

Research Needs

Ground Water

Completed and ongoing research related to ground water delineation demonstrates the breadth of methods and models available to decision-makers to support the task of delineating ground water recharge areas. Ground water delineation and modeling are relatively mature sciences, and techniques are available to fairly accurately predict flow.

In the past, sophisticated computer modeling tools were solely in the hands of hydrogeologists, whose consulting services were often outside the financial means of smaller ground water systems. One challenge is to put the latest computing technology in the hands of people doing assessments. The Center for Exposure Assessment Modeling (CEAM) within ORD is working to make a wide range of models and simulations readily available, from the user-friendly WhAEM model to sophisticated state-of-the-art simulation programs. Computers and models have increased in sophistication and ease of use, while prices have decreased.

Research should be focused on **developing robust and easy to use PC-based programs** that would allow decision-makers to input as much data as they have (from simple to complex) and whose delineation output is as accurate as possible based on the hydrogeologic situation, without hiring expensive hydro-geological services. Improved software, techniques, and training could help land use planners better understand ground water flow. In addition, research into model development should continue to stress the importance of improving the effectiveness of various ground water models. These types of developments can parallel efforts to make models more robust and easy to use.

It should be noted, however, that a great deal of technical expertise may be needed to acquire some of the necessary inputs, such as transmissivity or water table parameters. Some states require that this information be gathered and analyzed by licensed geologists or engineers. The accuracy of the delineation and model results are proportional to the resources and data needed for the model. Information in New Jersey's guidance for wellhead protection area delineation (Spayd, 1989) is a good example of making the best use of available data. Where a decision has been made to use a calculated fixed radius, less sophisticated inputs may be used, and user-friendly models may be appropriate. Training and education for model users may be needed; without proper training, incorrect inputs could generate bad model results.

Second, several research opportunities for expanding the hydrologic science of ground water delineations exist. For example, further research may be needed to investigate the **application of various tracers in ground water delineations**. Tracer studies are currently limited in that only the entry and exit points of the tracer can be identified, not the actual path within the aquifer the tracers take. Specific research needs include which tracers (and at what quantities) are most appropriate in various hydrogeologic situations or rock media, and improved detection equipment.

Third, better understanding of the **infiltration properties of various sediment types** would provide important information that hydrogeologists could use to better estimate precipitation infiltration in a variety of settings. The infiltration estimates used in mass-balance equations for ground water delineations are usually based on limited studies of precipitation infiltration through variably-saturated layers of overburden. For example, in glacial settings, this overburden may consist of lodgement or ablation till, lacustrine or marine clays, outwash, and ice contact deposits. Field studies would provide a better understanding of the properties of these materials and, therefore, better inputs for mass-balance equations.

Other research gaps related to ground water delineations include:

- Improved methods for ground water delineations in fractured and karst settings, which are the most vulnerable.

- Low-cost methods for age dating of ground water.

Surface Water

Many delineation techniques are available to watershed planners: fixed radii/distance upstream, buffer zones, time of travel, watershed segmentation, or conjunctive delineations. Often, however, managers do not have sufficient information or the understanding they need to determine which are the most useful, appropriate to the situation, cost-effective, or defensible. Research is needed on methodologies to help decision-makers select the delineation techniques that are most appropriate given local hydrology, threats, and their priorities for prevention actions. Research should be directed to developing decision-making tools that could help planners determine which delineation techniques are most appropriate for identifying the watershed areas most vulnerable to specific land uses (e.g., agriculture) or contaminants (e.g., organics).

Planners could also benefit from research into **ways to compare available delineation techniques**. Such comparison criteria would identify the strengths and weaknesses of different techniques in various situations, or where varying amounts of information on the watershed is available; data requirements vs. accuracy or uncertainty; and the costs, technical requirements, and benefits of various methodologies.

As with ground water delineations, research should focus on making powerful, low-cost **computing technology available to support watershed delineations**. The power of databases inherent in GIS is not readily used by typical decision-makers. Effort should be made to integrate available data layers and user interfaces to simplify the assessment process.

Research into **conjunctive delineation methods** is limited and should be expanded. If ways to perform these delineations can be developed successfully, this could support selection of management measures, including TMDLs under the CWA program.

Other research gaps related to delineation of surface water areas include:

- Research on scientifically based methods for delineating surface source water protection areas in large basins.

2.B. Inventories of Potential and Actual Contaminant Sources

An integral part of the source water assessment and protection process is the creation of an inventory of potential and actual contaminant sources and evaluation of their potential to adversely impact the source water of drinking water supplies. An inventory of these potential and actual contaminant sources can serve at least three important functions: (1) identify past, present, and future land use activities that may pose a threat to the drinking water supply; (2) obtain information on the locations of these potential and actual contaminant sources in relationship to drinking water sources; and (3) provide an effective way to educate the public regarding potential problems in their drinking water supplies.

Research Questions

What is the most efficient way to link disparate existing data on regulated point sources of contamination?

What cost-effective technologies can be used for an accurate and defensible listing and display of actual and potential sources of contamination?

> ***Research Needs...***
>
> ✔ Support contamination source inventories by linking data bases and using GIS.
>
> ✔ Refining bacterial source tracking technologies.

State of the Science

The first step of the contaminant source inventory is typically a compilation of available information on potential and actual contamination sources. Many data sources are readily available to initiate the inventory process. For example, facility level data can be found among the various databases developed and maintained by EPA's regulatory programs. Examples include EPA's Toxic Release Inventory (TRI) of chemical manufacturers and distributors and National Pollutant Discharge Elimination System (NPDES) waste water dischargers. State environmental and health departments may maintain useful data sets (e.g., underground storage tanks or septic systems). Local organizations, such as fire departments, may maintain data on users of certain hazardous substances. In addition, a large number of commercially available databases can provide locational and other attributes (e.g., industrial classification) of facilities at reasonable costs.

Because this data belongs to a variety of agencies and organizations, it may be stored in diverse ways. Examples include: GIS layers, tailor-made databases, Oracle platforms, spread sheets, or even paper files. The information they contain varies as well, such as locational data in a variety of formats (latitude/longitude, street address), amounts or types of chemicals stored, and data on chemical releases.

The next "layer" of the source inventory effort is to identify and map any additional land uses or activities that may not be cataloged in established databases but could still threaten drinking water supplies. This filling in the gaps has traditionally been done through ground surveys or field studies.

In 1991, EPA prepared a Technical Assistance Document on conducting contaminant source inventories for the wellhead protection process (EPA, 1991). This document described relatively "low tech" approaches to identifying potential contamination sources, including door-to-door and windshield surveys, and field studies.

The development of new technologies, such as the Global Positioning System (GPS), in recent years has provided ways to refine these data collections, interpret the information, and present the results in more comprehensive ways. Recently, source water managers have begun to supplement this process using newly available technologies, such as aerial photography and satellite imagery, GPS to precisely locate contamination sources, and GIS software to plot their location on maps of the delineated source water areas.

Bacterial source tracking (BST) is new methodology for determining the sources of fecal bacteria (e.g., from humans, livestock, or wildlife origins) in environmental samples, including water. BST can be used to match microorganisms to identify or quantify a particular source of contamination. However, the technology currently cannot distinguish between *types* of livestock, wildlife, or pets. Available methods for use in BST include: antibiotic resistance analysis (ARA), ribotyping, pulsed-field gel electrophoresis (PFGE), and polymerase chain reaction (PCR). It is an important tool in linking identified potential sources of contamination to actual contamination events. The Proposed Ground Water Rule advocates the use of viral and bacterial indicators for detecting fecal contamination. Analytical methods for fecal coliform and *E. coli* are becoming well established (see discussions in sections 2.C and 4.A).

Ongoing Research

Ongoing research by USGS, the American Water Works Association Research Foundation (AWWARF), and others is looking into identifying actual and potential sources of contamination and displaying their locations in a way that supports the susceptibility determination process. In one USGS research project, a pollution source inventory database is being developed to interface with an exposure assessment system to provide information that may be used in transport models and a risk characterization method to determine susceptibility.

With advancement in computer and telecommunication technologies, it is becoming increasingly easy and cost-effective to use GPS, GIS, and remote sensing technologies to develop an inventory of potential and actual contaminant sources within source water protection areas. Land use and land cover data from USGS have been generated using remote sensing techniques and are available for use with GIS software that can be installed and used on desktop computers. In addition, the availability of inexpensive GPS receivers (e.g., less than $200) has made it economical to obtain locational data for all facilities of interest. Furthermore, other remote sensing technologies such as geophysical surveys can be used to locate underground objects (e.g., abandoned wells). Additional information on the use of geophysical techniques to locate abandoned wells can be found in Section 3.M.

Research into further developing the science of bacterial source tracking is underway at Virginia Institute of Technology. (See Section 4.A for more on this research.)

Research Needs

Needed research for source inventories focuses on how information technology can be used to link available data and the use of GIS and GPS technologies. It appears there are many databases containing information relevant to identifying potential and actual sources of contaminants, although they are in a variety of potentially incompatible formats. Research is needed on developing efficient ways to **link disparate existing data on regulated point sources of contamination** and display it in a meaningful way.

Research should also focus on **identifying and developing inexpensive GIS and GPS technologies** for use by state and local decision-makers for an accurate and defensible listing and display of actual and potential point and nonpoint sources of contamination. With the advance in GPS and GIS technologies, it may be time to develop a user-friendly and low-cost method to more effectively provide source inventories that support subsequent source water assessment and protection efforts, such as susceptibility determinations and development of management measures.

Easy-to-use PC-based software packages could allow planners to map the locations of potential contamination sources from existing databases. Ideally, these data would be combined with those identified through local surveys and be compiled and displayed in a way that supports susceptibility determinations and management decisions. One such tool is a conversion or look-up table that links potential and actual contamination sources, contaminants, and analytical methods. Research into further developing this type of decision support tool may be needed. One example is SICView, a database program developed by EPA Region 2 for supporting facility inspection under the Underground Injection Control (UIC) program.

BST is an emerging science, and new research is needed to refine indicator technologies and develop their potential applications. **Additional research on BST** may be needed to determine which of the available technologies is the best, or a "toolbox" of source tracking methodologies that allows managers to pick technologies based on the specific situation. Furthermore, research into the development of the technology to discriminate between specific livestock or wildlife species should continue. See also the discussion of applications of indicator technologies to ground water sources on page 81, in Section 4.A.

On using viral and bacterial indicators for detecting fecal contamination, research is needed on various indicator organisms to prove their efficacy and make these technologies more cost-effective.

Other research gaps include:

- Research on the release of contaminants from soils is needed in order to assess the potential for source water contamination as a result of contaminated sediment. (See Section 2.C on susceptibility determinations for further discussion.)

2.C. Susceptibility Determinations

Susceptibility assessments are conducted to determine the vulnerability of a public water system (PWS) to contamination of its source water by contaminant sources. EPA requires states to conduct intra-system susceptibility determinations as part of their source water assessment programs, and encourages states to conduct inter-system comparison. Intra-system susceptibility is the relative susceptibility of a PWS to different potential contamination sources or different contaminant categories. Inter-system susceptibility is the relative susceptibility of all PWSs in a state.

Research Questions

What are the most cost-effective and accurate methods to identify actual current sources of contamination of source waters?

What is the most accurate method to describe the relative threats from different sources of contamination to a public water supply?

What is the most accurate method to describe the relative threats from various sources of contamination to multiple PWS resource-wide areas?

What is the most accurate method to rate and rank PWSs against each other on a susceptibility scale?

Research Needs...

- ✔ Comparing the accuracy and cost-effectiveness of susceptibility determination methods in use for drinking water sources.
- ✔ Consistent methods for use in area-wide assessments of specific geologic and geographic settings.
- ✔ Constructing confidence bounds for susceptibility determination results.

State of the Science

The overall utility of a susceptibility (or vulnerability) assessment is highly dependent on the scale at which it is conducted, the scale at which the data are available, and the scale at which results are displayed. In general, susceptibility determinations take into account the following factors: source water hydrology and hydrogeology, inherent contaminant characteristics, properties of potential contaminant sources (e.g., location, release likelihood, and mitigation effectiveness), and the structural integrity of the water system. The results of a susceptibility analysis will be one or more of the following:

- An absolute measure of the potential for contamination of the water supply.
- A relative comparison of contaminant sources within the source water protection area.
- A relative comparison to findings of other assessments.
- Some other result that would provide for the protection and benefit of the water supply.

Source Water Susceptibility Factors

Source Water Hydrology and Hydrogeology

Whether a drinking water source is surface water, ground water, or GWUDI strongly associates the range of contaminants to which it is susceptible. Surface water is generally susceptible to a wider range of contaminants than ground water. Similarly, GWUDI is more susceptible than deep aquifers to contaminants introduced at the land surface. Deeper aquifers, however, may be more susceptible to naturally occurring inorganic chemicals (IOCs) and radionuclides that might not be present in shallow aquifers or at the surface.

Surface Water

Surface water systems are generally considered to be sensitive to any contaminant with a source within their drainage area, partly because many contaminants originate from surface sources (USEPA, 1999b; Hallberg et al., 1997; Hallberg et al., 1996; Larson et al., 1997). For example, synthetic organic chemicals (SOCs) such as pesticides originate at the surface, as do animal and human wastes that are the primary sources of pathogens. Surface waters are also susceptible to atmospheric deposition of contaminants through dryfall or precipitation (Hochstedler et al., 2000; Lynch and Dise, 1985; Majewski and Capel, 1995).

Important natural mitigating influences that may be present between surface contaminants and ground water, especially the soil and/or confining units, do not protect surface waters. Ironically, the functions of the subsurface that protect ground water, such as adsorption and filtration of contaminants, may make contaminants available to surface water bodies through runoff, "throughflow" (shallow ground water flow), and erosion of contaminated sediments. The potential for dilution of contamination, however, is much greater for surface water systems than for ground water systems because most precipitation reaching the land surface moves to surface water. Only a small percentage of precipitation infiltrates the land surface and moves through the ground water system (Winter et al., 1999).

Initial results from the USGS's National Water Quality Assessment (NAWQA) program illustrate the comparative sensitivity of surface water systems with regard to pesticides. More than 95 percent of surface water samples detected at least one pesticide. In contrast, only 50 percent of ground water samples had detects (Miller and Wilber, 1999). A study examining hydrologic aspects of pesticide transport in an Iowa stream also found surface waters to be more sensitive (Squillace and Thurman, 1992).

Ground Water

Compared to surface water systems, assessing the susceptibility of an aquifer is more complicated. Natural influences such as the unsaturated zone, intermediate geologic formations, and aquifer depth strongly influence whether or not surface contaminants will reach an underlying aquifer. Other important considerations include aquifer thickness, mineralogy, and lithology.

The Unsaturated Zone

The unsaturated zone or vadose zone, is the subsurface area between the land surface and the saturated zone. Its components include the soil zone, immediately beneath the land surface, and the intermediate zone, which lies between the soil zone and the saturated zone (Heath, 1983). These unsaturated zones have an important influence on contaminant transport and degradation, and therefore, significantly influence ground water susceptibility to surface contamination (Robins, 1998). For example, the unsaturated zone's thickness affects contaminant travel time and degradation, and the total particle surface area available for sorption (Burkart and Kolpin, 1993).

The soil zone, where present, controls the movement of water between the land surface and the subsurface. Burkart and others (1999) found soil permeability within 2-km of their study wells to have a significant influence on concentrations of agrochemicals in the well water. Other soil properties also influence ground water sensitivity. Typically, soils with high clay and/or organic matter content increase the sorption potential of a contaminant. Soil also harbors microbes that are the primary degradation route for many contaminants. Soil conditions that increase soil microbial activity increase degradation of the compound. For example, high soil temperatures and high soil moisture may increase microbial degradation of some contaminants (EXTOXNET, 1998).

The intermediate zone impacts contaminant fate and transport as well. Both the sorption value of the intermediate zone's materials, and the total surface area available for sorption (indicated by porosity), determine its sorption capacity (Bekesia and McConchieb, 2000). Also, organic carbon and microbes can be important in the intermediate zone, though generally far less so than in soil.

Intermediate Geologic Formations

A low-permeability confining layer that slows or precludes vertical ground water flow significantly impacts contaminant mobility to an aquifer. Unconfined aquifers are comparatively more sensitive to surface contaminants because their recharge is more directly connected, and responsive, to the events at the land surface (Burkart and Kolpin, 1993; Hallberg, 1989a; Liu et al., 1996). In addition, research in New Jersey has found a strong relationship between a PWS well's susceptibility to contamination and the distance of the well from the recharge area of the confined aquifer in which it is screened (Vowinkel et al., 1994).

Aquifer Properties

Aquifer depth and thickness have an important influence on sensitivity. The lithology and mineralogy of the aquifer unit are also important. Aquifer depth and thickness together influence the length of the flow path, and the time of transport, for contaminated recharge to reach an aquifer, or for contaminated ground water to reach greater depth within an aquifer. A longer flow path, either through saturated or unsaturated material, provides increased opportunities for degradation and/or sorption of contaminants (Burkart and Kolpin, 1993). Numerous contaminant occurrence studies reflect this (Burkart and Kolpin, 1993; Druliner and McGrath, 1996; Hallberg et al., 1996; Kolpin et al, 1997b; Rupert, 1998; Ryker and Williamson, 1996; Stackelberg et al., 2000; Vowinkel et al., 1994). Longer flow paths, and hence greater time of travel, also indicate that ground water in deep aquifers is older, perhaps recharge from a time before anthropogenic contaminants were introduced at the land surface. Important exceptions to this depth and contamination relationship are karst aquifer systems and inorganic chemicals that occur naturally as a consequence of aquifer mineralogy (Hallberg et al., 1996; USEPA, 1999b).

Studies have also demonstrated how aquifer mineralogy and lithology influence susceptibility. The presence of clay minerals and/or organic carbon in aquifer materials may retard movement of contaminants by adsorption. Other mineralogic properties can affect chemical transformations of contaminants. Lithology is an important determinant of aquifer permeability and, in turn, contaminant mobility. Highly permeable aquifers such as those made up of unconsolidated sand and gravel deposits are more susceptible to contamination. On the other hand, marine clays have much lower hydraulic conductivities and form barriers to contaminant movement. Similarly, massive igneous and metamorphic rocks have very low hydraulic conductivities. Nevertheless, most consolidated rocks have water-bearing voids present from the time of formation and possess some degree of permeability (Domenico and Schwartz, 1998). Consolidated rocks may, however, have fractures, solution cavities (e.g., karst), or other preferential flow pathways where subsurface flow is rapid (Hallberg, 1989a; Hallberg et al., 1996; Mueller et al., 1995; USEPA, 1999b).

Ground Water/Surface Water Interactions

Discrete areas where ground water and surface water are in hydraulic connection can influence source water susceptibility to contamination in unique, and sometimes complex, ways (Winter et al., 1999). If a public water system relies upon a surface water source, the system should consider the quality of the aquifers that discharge to it. Similarly, PWSs using GWUDI need to be concerned with the quality of nearby surface waters (USEPA, 1998; USEPA, 1999a). Ground water/surface water interactions also have important implications for source water delineations and must be considered during that step in the source water assessment process (see Section 2.A).

Approximately 40 percent of perennial streams' discharge in the United States is supplied by ground water discharge (USEPA, 1998), although there is considerable variation by physiographic and climatic setting (Winter et al., 1999). Ground water discharge is the stream's baseflow that sustains it through dry periods. After many days without rainfall, the hydraulic head in a stream drops below the head in the adjacent alluvial aquifer. When this happens, the hydraulic gradient between the alluvial aquifer and the stream dictates flow from the aquifer to the stream. Research has demonstrated that the persistence of many pesticides and their degradates in streams during baseflow periods is attributable to contaminated ground water discharge (Squillace et al., 1993; Hallberg, 1989a). Furthermore, ground water discharge is often the source of high nitrate concentration in surface water systems (Hallberg, 1989b). The impacts of ground water on surface water are also controlled by many local factors such as geology, hydrology, climate, and water use.

Ground water quality can also be influenced by surface water. Shallow aquifers without an impermeable stratum between the aquifer and the unsaturated zone are especially sensitive. These "unconfined" aquifers are at atmospheric pressure, allowing infiltrating precipitation and surface runoff to reach them relatively easily and quickly. Many contaminants discharged or applied at the land surface, for example pesticides, are transported to shallow aquifers by this recharge water. Shallow, unconfined, alluvial aquifers are among the most sensitive ground water settings (Hallberg, 1989a; Hallberg et al, 1996; Kolpin et al., 1997a). Near-surface karst or fractured bedrock aquifers are similarly affected. Both of these hydrogeologic settings may provide preferential flow paths for infiltrating precipitation and surface runoff, and any associated contaminants, to rapidly reach ground water.

Surface water may also influence ground water at the streambank interface during flood events. As river stages increase, hydraulic heads in the stream may reach a point where they become greater than those in the adjacent alluvial aquifer, inducing flow from the stream to the aquifer. Since high streamflow events are primarily composed of overland flow that picks up surface contaminants in the basin, it is not uncommon for these discharges to carry high contaminant concentrations. This is especially true for agricultural basins where the wet season and pesticide use are typically coincident (Squillace and Thurman, 1992). Recent research confirms that high streamflow events can be responsible for contaminant concentration spikes in adjacent alluvial aquifers (Squillace et al., 1993; Wang and Squillace, 1994; Liu et al., 1996). Researchers have also noted that riverbank filtration systems may experience higher contaminant concentrations during flood events in relation to increased head gradients (Gollnitz, 1999; Ray, 2001a). Riverbank filtration is a surface water treatment process that uses the bed and bank of a river or lake, and the adjacent aquifer, as a natural filter. Contaminant spikes in riverbank filtration wells during flood events are also thought to be related to flood scour, and the associated removal from the surface water/ground water interface of fine grained materials that plug pores and impede contaminant transport to the alluvial aquifer (Gollnitz, 1999; Ray, 2001a; Ray, 2001b).

Surface water quality may also directly influence ground water quality in drier climatic regions and in certain settings in humid regions where runoff from a rainfall event may flow down a dry stream channel and then infiltrate the stream bed. In these landscapes, ground water is at greater depth and not in direct connection with the stream.

The susceptibility of drinking water supplies to contamination may differ depending on the degree of ground water/surface water interaction and the direction of influence (i.e., surface water on ground water, or vice versa). The influence of ground water on surface water is important in the development of TMDLs. EPA and USGS have examined the influences of ground water on surface water quality (i.e., the discharge of contaminated ground water to surface water); however, this research has been limited due to the localized nature of the factors that control surface water and ground water interaction, and the spatial and temporal variability of the relationship.

Spatial/Temporal Hydrologic Considerations

Some aspects of source water hydrology and hydrogeology have uniquely spatial and temporal implications that merit special mention here. For example, weather varies spatially and temporally, which controls two critical components of the hydrologic system: precipitation and evapotranspiration. Other hydrologic controls that vary through space and/or time include surface and ground water travel times; basin relief, size of the watershed, and geology; and ground water pumping.

Climate

Climate most directly impacts source water contamination susceptibility through its influence on contaminant transport via overland flow and/or recharge. Climate also significantly affects land use and contaminant use, which in turn influence susceptibility.

At most locations in the mid-latitudes, precipitation is unevenly distributed throughout the year. Not surprisingly, many contaminant occurrence studies in the midcontinental U.S. have observed a distinct seasonality to surface water detections, especially for pesticides (Correll et al., 1999; Larson et al., 1997; Larson et al., 1999; Squillace and Thurman, 1992; USEPA, 1999b). Peak pesticide use is also usually coincident with peak runoff/recharge periods (i.e., in the spring). Shallow, unconfined ground water and karst aquifer systems are also influenced by seasonal pulses in contaminant concentrations (Hallberg and Keeney, 1993; Hallberg, 1989a; USEPA, 1999b). Deep aquifers are not similarly affected because longer travel times and attenuation dampen seasonal impacts (USEPA, 1999b).

Climate's influence on the temporal variability of contaminant occurrence operates at other scales, including annual-scale (Hallberg, 1996) and the event-scale (i.e., first-flush during storms). Contaminant occurrence spikes in surface and shallow ground water are well known after individual runoff events. An obvious example is urban storm water in which concentrations of SOCs, volatile organic chemicals (VOCs), metals, and sediments are elevated during first flush (Waschbusch, 1996). Increased concentrations of pathogens are also observed after runoff events (Atherholt et al., 1998).

Recharge rates, evapotranspiration rates, and overland flow also vary spatially related to changes in climate. Variations are attributable to the regional dominance of large-scale atmospheric circulation features and/or topography. For example, in the upper Midwest, rainfall peaks in spring because at that time mean frontal boundaries between cool, dry, continental air masses and warm, moist air masses from the Gulf of Mexico are positioned over the region. The situation on the southwest coast (S. California) is different. Movement of large-scale atmospheric circulation features in that region induces precipitation peaks in the winter, with little to no rainfall during the rest of the year. Not surprisingly, contaminant occurrence study data for surface waters in these two regions reflect these temporal differences (Poletika et al, 2000; Squillace and Thurman, 1992).

Hydrologic Response

The time elapsed between a basin rainfall event's central mass volume and the peak runoff rate observed at a given point in the stream (e.g., a surface water intake) is known as the time lag. It typically occurs on relatively short time scales (e.g., hours, days, weeks) and is affected by factors such as basin size, shape, local relief, soils, land cover, and drainage density (Focazio et al., 1997). This phenomenon is related to the watershed's time-of-concentration, that is, the time it takes for runoff from the most distant point in a watershed to reach a given point. The time lag can be thought of as a weighted average of the individual times-of-concentration for the basin's sub-watersheds (Kent, 1972). In many watersheds, streamflow contaminant concentrations at a given point are highest just before the runoff peak, probably because contaminants get concentrated in the initial stages of runoff generation known as the "first flush," which typically arrives just before the runoff peak.

For aquifers, the time lag for contaminants to reach ground water from the surface is usually longer, especially for deep aquifers overlain by thick unsaturated zones and/or confining units. Ground water in some deep aquifers may be old, representing recharge that entered the recharge area hundreds, or even thousands of years ago (Burkart and Kolpin, 1993; Hallberg et al., 1996; Spurlock et al., 2000; USEPA, 1999b; Vowinkel et al., 1994).

Hydrologic response for surface and ground water varies spatially too. For example, ground water far down-dip from the outcrop area of a confined aquifer may be too old to be contaminated while parts of the same aquifer are contaminated due to their proximity to the recharge area (Vowinkel et al., 1994). Also, differences in the mineralogy of regional geologic formations influence susceptibility to certain inorganic chemicals such as arsenic (Miller, 2000). Finally, unsaturated zone thicknesses are highly variable over the landscape (Bekesia and McConchieb, 2000).

Basin relief, along with basin geology, determines recharge areas and rates as well as the magnitude of overland flow. The geology also affects ground water and surface water chemistry. For example, researchers working in Shenandoah National Park found surface water alkalinity to vary with basin geology. The alkalinity, in turn, determines stream sensitivity to acid precipitation (Lynch and Dise, 1985). Basin size is also significant. Research in the Midwest found small basins to have the highest concentrations of surface contaminants during peak runoff events (Baker and Richards, 2000; Squillace and Thurman, 1992). Concentrations tend to attenuate and decline downstream. National contaminant occurrence work shows similar results (Miller and Wilber, 1999). Annual mean surface water nitrate concentrations in Midwestern basins ranging in size from 0.1 to 237,000 km^2 also show decreasing concentrations with increasing basin size for a given percentage of row crop agriculture in a basin (Schilling and Libra, 2000).

Ground water pumping may indirectly influence ground water susceptibility through space and time. Excessive pumping can increase a well's contributing area, increasing the possibility of contamination from more surface and sub-surface sources (Franke et al., 1998). Pumping may also alter ground water flow patterns, or induce surface water infiltration, bringing increased risk of ground water contamination (Adams and MacDonald, 1998; Liu et al., 1996; Squillace and Thurman, 1992). Duncan and others (1991) documented induced infiltration of contaminated

Platte River water to the adjacent alluvial aquifer near Lincoln, Nebraska as a consequence of ground water pumping.

Contaminant Fate and Transport

Groups of contaminants with similar environmental behavior are often analyzed and regulated together. VOCs, SOCs, IOCs, radionuclides, sediments, and biological contaminants are commonly recognized categories with similar fate and transport properties that determine, in part, the susceptibility of source water to contamination.

<u>Volatile Organic Chemicals</u>

VOCs are a subset of the organic contaminants that evaporate relatively easily when exposed to air. Once in the atmosphere, they may break down further or return to the earth through dryfall or precipitation (Majewski and Capel, 1995). VOCs are commonly used in fuels, pesticides, industrial degreasers, and as solvents in paints and paint thinners. Some are used for dry cleaning or in synthetic polymers such as polyacrylamide and polyvinylchloride (PVC) (USEPA, 1999b).

Many VOCs have low water solubilities and form non-aqueous phase liquids (NAPLs) that are categorized by their density relative to water. NAPLs with densities less than water are termed light non-aqueous phase liquids (LNAPLs) while those with densities greater than water are called dense non-aqueous phase liquids (DNAPLs).

LNAPLs are more common in surface water and shallow ground water because their sources, such as gasoline and other petroleum products, are usually leaked or spilled at the land surface and they tend to float on water surfaces (USEPA, 1999b). LNAPLs can also enter ground water through leaking underground storage tanks and other sources, but their density makes their occurrence more likely in shallow rather than deep ground water (USEPA, 1999b). In surface waters, LNAPLs are often at low concentrations given their volatility and contact with the air (USEPA, 1999b). DNAPLs, such as trichloroethylene (TCE), are heavier than water and sink in the water column. They tend to concentrate at impermeable layers that form the lower boundaries of aquifers.

Because most VOCs are associated with industrial/urban applications and vehicle use, urban and suburban areas are most vulnerable to them (Daly and Lindsey, 1996; Miller, 2000; Squillace et al., 1999). VOCs may occur in less densely populated areas as a consequence of fuel spills, pesticide applications, or other types of releases.

<u>Synthetic Organic Chemicals</u>

The broad group of SOCs includes pesticides and polychlorinated biphenyls (PCBs). Pesticides have been widely used in agriculture since the 1960s, and also have suburban and urban applications. PCBs were commonly used in the 1960s and 1970s in transformers and capacitors. Because of their persistence, PCBs are still frequently detected in the environment, even though most production and uses have ceased because of their toxicity (Domenico and Schwartz, 1998).

Data have accumulated regarding the occurrence and distribution of pesticides in water (Barbash and Resek, 1996; Hallberg, 1989a; Larson et al., 1997; Majewski and Capel, 1995). Applied at the land surface, pesticides tend to occur most frequently in surface water and shallow ground water (USEPA, 1999b). The environmental fate and behavior of individual pesticides, however, varies considerably. The complex interaction of key properties such as volatility, solubility, sorption potential, and degradation rate largely determines a pesticide's occurrence, distribution, and persistence. For example, a pesticide that does not volatilize, is relatively soluble in water, and has a low potential to sorb to sediments is highly leachable and thus a threat to ground water. Moreover, if its primary degradation routes are through photolysis at the soil surface and soil microbial degradation, it is likely to persist if it reaches the ground water.

Inorganic Chemicals and Radionuclides

Most inorganic chemicals are naturally occurring constituents of the earth's crust, so they are ubiquitous in the environment and, as a group, are often detected more frequently than SOCs and VOCs (Hallberg et al., 1996). They commonly occur in surface and ground water, with concentrations usually higher in ground water because of its frequent contact with bedrock and unconsolidated minerals (USEPA, 1999b). Deep, "old" ground water often has the highest concentrations because it has had considerable time to accumulate many dissolved constituents from the surrounding aquifer materials. An important exception is nitrate, which is more prevalent in shallow ground water because it forms in the soil through microbial metabolic nitrification activity (Hallberg et al, 1997), and is often related to the use of nitrogen fertilizers, handling of manures, or disposal of sewage.

Radionuclides, unstable radioactive elements, also occur naturally and at a wide range of concentrations. Aquifer lithology, stratigraphy, and recharge chemistry significantly influence radionuclide occurrence (Hallberg et al., 1997; Szabo and dePaul, 1998).

Sediments

Turbidity creates aesthetic problems for drinking water and increases drinking water treatment costs (Hallberg, 1996). Even more important, inorganic and organic sediments are transporters and reservoirs for other contaminants (Correll et al., 1999; Larson et al., 1997). Many contaminants with moderate to high sorption potential are carried to surface waters via runoff-transported sediments (Correll et al., 1999; Squillace and Thurman, 1992). This is especially true for hydrophobic organochlorine pesticides (e.g., DDT and dieldrin), many of which have been discontinued for agricultural use in this country (USGS, 1999; USGS, 2000). The residence times for contaminants stored in bottom sediments vary considerably depending on the disturbance regime. Bottom sediments release contaminants during high energy storm events that create hydrologic disturbance, through bioturbation, or by diffusion from sediment pore water to the overlying water body (Larson et al., 1997). Bottom sediments may act as contaminant sources to the overlying water for many years and decades.

Anthropogenic activities in a watershed can enhance erosion of sediments and subsequent sedimentation. For example, agriculture often increases watershed sediment production.

Anthropogenically accelerated erosion and sedimentation will likely increase surface water turbidity in the watershed and can compound problems with associated adsorbed contaminants.

Biological Contaminants

Biological contaminants include pathogenic bacteria, protozoa, and viruses. Surface waters and shallow ground water are the most susceptible to these contaminants partly because the sources, primarily human and animal wastes, usually occur at, or near, the land surface (Francy et al., 2000; Hancock et al., 1998; States et al., 1997). Other important factors include subsurface environmental conditions that discourage, or preclude, migration of pathogens beyond the soil zone. Sand- or finer-size sediments are capable of filtering some pathogens out of recharge, or significantly impeding migration so that transformation processes or adsorption may take place. Furthermore, the organic matter on which most pathogens survive is also not present at depth because of filtration, adsorption, or degradation (Domenico and Schwartz, 1998).

Recent research in a number of National Water Quality Assessment (NAWQA) study units illustrates the greater vulnerability of surface water and shallow ground water to pathogens (Francy et al., 2000). Ninety-nine percent of the stream samples had detections of total coliforms (indicators of possibly pathogenic contamination). Ninety-seven percent had *E. coli* detections, which more definitively indicates fecal contamination. *C. perfringens*, used in this study as a surrogate for stress-resistant organisms such as *Cryptosporidium* or *Giardia*, was detected in seventy-three percent of the stream water samples. Ground water samples had fewer detections of microbiological indicators, with percent detections of 20, 1, and zero for total coliforms, *E. coli*, and *C. perfringens* respectively (Francy et al., 2000).

Deeper ground water can be contaminated by pathogens through surface runoff entering poorly constructed wells. Biological contaminant sources that discharge below the protective unsaturated soil zone (e.g., a poorly constructed on-site septic system) can also contaminate ground water (USEPA, 2000; 65 FR 30194). Moreover, some pathogens found in human sewage, including microspordia and viruses, are small enough to reach vulnerable, deeper ground water.

Contaminant Degradation Products

Many contaminants are broken down in the environment to simpler compounds, but some of the degradates may still be related to the parent compound structurally and toxicologically (Hallberg, 1989a; Liu et al., 1996; Spurlock et al., 2000). Degradation routes include microbial metabolic activity in soil and water, photolysis from soil surfaces, and aqueous photolysis (Kolpin and Kalkhoff, 1993). Though parent compounds may be present in source water in low concentrations or for only a short time, equally harmful degradates might be in greater abundance and persist for longer periods (Hallberg, 1989a; Liu et al., 1996; Kolpin et al., 1997b; USGS, 1999).

Some metabolites are more water soluble than their parent compound, which can increase their mobility in the subsurface. Two metabolites of the pesticide atrazine, deethylatrazine (DEA) and deisopropylatrazine (DIA), are more water soluble than the parent compound and often occur with similar, or greater, frequency in ground water (Barbash and Resek, 1996; Kolpin et al., 1998, 2000; Larson et al., 1999; Liu et al., 1996).

Degradates of tetrachloroethylene (PCE), a contaminant used historically in dry cleaning and regulated in drinking water, are themselves regulated by National Primary Drinking Water Regulations (NPDWRs). In anaerobic conditions, PCE degrades, through a dechlorination sequence, to trichloroethylene (TCE), which in turn degrades to dichloroethylene (DCE), and finally to vinyl chloride. With the exception of vinyl chloride, all of these compounds are DNAPLs that are particularly threatening to ground water (Domenico and Schwartz, 1998). Vinyl chloride, however, is very toxic, and the PCE degradation sequence is an example of a parent compound (e.g., PCE) yielding a more toxic degradate (e.g., vinyl chloride).

Contaminant Sources

Source water susceptibility varies spatially, and through time, with contaminant sources. A good indicator of contaminant sources, especially for nonpoint source contaminants, is land use. VOCs are detected more frequently, and in higher concentrations, in aquifers underlying urban areas (Miller, 2000; Squillace et al., 1999; Stackelberg et al., 1997). Broadly speaking, urban areas are also associated with a different set of pesticides than agricultural areas (Kolpin et al., 1998, 2000; Larson et al., 1999; Squillace et al., 1999). NAWQA results for surface waters show that agricultural areas have greater detections and concentrations of herbicides while urban basins have higher detections and concentrations of insecticides (Larson et al., 1999; Miller, 2000; Stamer and Wieczorek, 1996).

Within the two broad categories of land use, urban and agricultural, contaminant occurrence is sensitive to small-scale changes in use and differences in intensity of use. For example, pesticide occurrence in agricultural areas varies with crop type (Kolpin et al., 1998; Larson et al., 1999) and the intensity of irrigation (Burkart and Kolpin, 1993; Kolpin, 1997). Nitrate concentrations in ground water vary by region because of differences in intensity of agriculture, intensity of fertilizer use, and irrigation (Mueller et al., 1995). Population density is a predictor of the probability of VOC occurrence in ambient ground water (Squillace et al., 1999) and a predictor of anthropogenically derived lead and zinc concentrations in surface waters (Miller, 2000).

Evaluating source water susceptibility by examining basin land use and contaminant use can be confounded by atmospheric transport of contaminants. Anthropogenic pollutants are sometimes detected in undeveloped watersheds as a consequence of atmospheric transport. Researchers investigating pesticides in the atmosphere have found evidence for long range transport (Goolsby et al., 1994; Majewski and Capel, 1995). Data confirming atmospheric pesticide transport over lesser distances are also available (Hochstedler et al., 2000; Seiber and Woodrow, 2000). Other anthropogenically released pollutants, for example mercury or inorganic manganese from industrial emissions, are transported as particulate matter in air (ATSDR, 1997).

Structural Integrity of Wells and Surface Water Intakes

Improperly cased and sealed wells increase the susceptibility of ground water sources. Surface water or shallow ground water carrying pesticides, VOCs, pathogens, or other contaminants may rapidly enter deep aquifers through the conduit provided by such a well (Franke et al., 1998; USEPA, 2000; 65 FR 30194). For PWSs not required to treat their ground water, this poses an immediate threat to the safety of the finished drinking water.

The structural integrity and position of surface water intakes, and the infrastructure transporting source water from surface water intakes and wellheads, is also an important factor for susceptibility analysis. Breakages in this infrastructure may allow contamination of the source water. In addition, corrosion of intakes and cross-connections to the distribution system threatens source water both indirectly, by compromising system integrity, and directly through the production of toxic corrosion by-products (Craun and Calderon, 2001).

State Susceptibility Assessment Methods

Susceptibility determinations required of states as integral parts of source water assessments should take into account source water hydrology and hydrogeology, inherent contaminant characteristics, properties of potential contaminant sources, and the structural integrity of the water system. To accomplish this, states have modified or built upon existing susceptibility and sensitivity assessment methods, or developed new methods. A decade ago, EPA reviewed a broad spectrum of ground water sensitivity and susceptibility assessment methods (USEPA, 1993). This section focuses only on the state efforts initiated after the source water assessment programs were mandated by the 1996 SDWA Amendments.

Intra-system Assessments

EPA requires states to conduct intra-system susceptibility determinations as part of source water assessments. Intra-system determinations assess the relative susceptibility of a PWS to different potential contamination sources, or different contaminant categories, within the PWS's source watershed or capture zone. State intra-system susceptibility determination results are typically in the form of a relative ranking scale (High-Medium-Low) or a numerical score. Rankings or scores may be derived through decision trees, matrices, or a narrative prioritization.

Many states assess the susceptibility of surface water and ground water sources differently, recognizing their inherent hydrologic differences (e.g., AZ, CT, MA, ME, NH, PA, TX, WI). Other states make no distinction between source water types for their susceptibility determinations (e.g., NY, RI, SD, and VT). If a state does have separate susceptibility approaches for ground and surface water sources, they may apply both methods to sources that are designated GWUDI (e.g., WI).

States have developed a wide variety of intra-system susceptibility determination methods of varying complexity and sophistication. Most, however, consider the four factors outlined above. The State of Massachusetts is one exception. Massachusetts does not consider well integrity in its susceptibility determinations. The state details its rationale in its EPA approved SWAP plan, reasoning, among other things, that only three PWS wells in the state are in confined settings as the state defines them. Therefore, most of the state's wells are in unconfined settings that have already been designated as highly vulnerable by the state, obviating the need to investigate well integrity (MADEP, 1999).

A few states adopt or modify existing methods. Pennsylvania, for example, uses the DRASTIC methodology as one component of its ground water susceptibility analysis approach (PADEP, 2000). DRASTIC is a sensitivity assessment method (i.e., it evaluates the ability of a potential contaminant to migrate to an aquifer, based on hydrogeologic characteristics alone–contaminant sources are not considered) developed in the late 1980s and supported by EPA (Aller et al., 1987). South Dakota bases its susceptibility determination method loosely on EPA's Superfund program's Hazard Ranking System (HRS; SDDENR, 1999). The HRS method is conceptually similar to the source water assessment program's susceptibility assessment because it considers both hydrogeologic factors and contaminant sources (e.g., contaminant characteristics) (USEPA, 1990; 55 FR 51531). In Texas, the GLEAMS model is being used to estimate pesticide losses for a variety of soils and climates as one component of its assessment (TNRCC, 1999).

Some states have partnered with other agencies to develop susceptibility determination methods. The Texas Natural Resource Conservation Commission cooperatively developed their methods with the Texas District of the USGS Water Resources Division (TNRCC, 1999). Rhode Island and Virginia are working with USGS personnel in their states as well (DeSimone and Ostiguy, 1999). States are also trying to coordinate their susceptibility determination efforts with previous, ongoing, and future work. For example, many states will build upon efforts already completed or underway as part of state wellhead protection programs (e.g., AZ, MA, SD, TX, and WV) and/or other existing source water protection initiatives. Some states, such as Massachusetts, are anticipating future regulatory synergies. For example, Massachusetts is delaying finalization of its susceptibility determination process for microbial sources of contamination to coordinate SWAP efforts with EPA's Ground Water Rule (GWR) (MADEP, 1999). As proposed, the GWR will require hydrogeologic sensitivity assessments for microbial contaminants.

Inter-system Assessments

EPA does not require, but does encourage, statewide comparisons of PWS sources' overall susceptibility–inter-system susceptibility determinations. These assessments will assign an overall susceptibility rating to each PWS in a state, allowing comparison among systems and enabling prioritization for staffing and funding.

Most states either do not plan to conduct inter-system susceptibility determinations, or did not address the issue in the SWAP plans submitted to EPA. Of the states that are planning to conduct the inter-system assessments, all intend to rank the systems categorically with designations of "high-medium-low," or simply with "yes/no" or "susceptible/not susceptible" rankings. States will arrive at these designations through either numerical scoring systems or narrative approaches. South Dakota, for example, proposes that it may arrive at an overall susceptibility determination for a PWS source by simply averaging the numerical intra-system susceptibility scores for each potential contaminant source (SDDENR, 1999).

Area-wide (Regional) Assessments

Some states will reduce the resources needed to conduct source water assessments by conducting area-wide assessments. Area-wide assessments are appropriate when multiple PWS sources have uniform conditions (e.g., geology) that allow for common susceptibility determinations (WIDNR, 1999). For example, a state may want to designate as susceptible all ground water PWSs in a karst region. Texas plans to conduct area-wide assessments for multiple surface water systems with intakes in the same reservoir, and for multiple ground water systems sharing the same contributing area (TNRCC, 1999).

Area-wide assessments may also be especially well suited to certain PWS classes, for example Transient Non-Community Water Systems (TNCWS). The thousands of TNCWSs in Connecticut are generally low yielding, bedrock well systems for which few site-specific data are available. The State of Connecticut notes that conducting source water assessments for all of these small systems within the SWAP time frame is not feasible. Therefore, they have proposed area-wide assessments for groups of TNCWSs with uniform hydrogeologic conditions (CDPH and CDEP, 1999). Many states also assert that the primary concern for TNCWSs is exposure to contaminants that produce acute responses (i.e., pathogens; ODEQ and OHD, 2000). As such, they intend to only assess TNCWSs for microbial contamination susceptibility (i.e., a "differential assessment"). The State of Wisconsin recognizes both uniform geologic conditions and PWS class characteristics in its decision regarding the most appropriate application of area-wide assessments. In Wisconsin, an area-wide assessment may be warranted when multiple TNCWSs draw water from aquifers protected by a confining layer of known regional extent, reasoning that TNCWSs tend to have low pumping capacity and therefore reduced ability to draw pathogens through a confining unit, provided that the TNCWS wells are properly constructed (WIDNR, 1999).

Ongoing Research

Current research efforts applicable to susceptibility assessments are practically innumerable. Ongoing academic research in the sub-disciplines of aqueous geochemistry, contaminant hydrogeology, aquatic toxicology, watershed hydrology, remote sensing and geographic information systems, and many more, bear on the factors influencing source water susceptibility. Federal, state, and local government agencies and laboratories are also moving ahead on many research fronts pertinent to source water susceptibility, especially with regard to fate and transport of contaminants in surface and ground waters. (Note: Some ongoing research efforts by USGS, states, and national laboratories are described under "ongoing research" in the susceptibility determination section of Appendix B.) Of special note are the state susceptibility assessment methods that are still being refined, and related efforts by the USGS. For example, the USGS and the Virginia Department of Health are currently in the process of age dating Virginia's ground water PWS sources to screen for systems that will need more detailed source water assessments (USGS, 2001a).

Some other ongoing Federal agency activities have particular significance for improving regional susceptibility analyses (important for multi-jurisdictional or multi-system assessments). As part of the NAWQA program's High Plains Regional Ground Water Study, the USGS is examining statistical relationships between variables such as land use and geology, and nitrate concentration. These relationships may then be used to determine the vulnerability of ground water to present and future anthropogenic activities within the High Plains study area (USGS, 2001b).

ORD is developing a methodology for assessing ecological risk at regional scales through the Regional Vulnerability Assessment (ReVA) program. Unlike other applications discussed above, vulnerability in ReVA is not restricted to water resources. This effort attempts to integrate information on ecosystem sensitivity, environmental stressors, resource valuation, and socio-economic drivers of both ecosystem stress and ecosystem management policy. Sensitivity includes hydrogeologic sensitivity as well as other factors influencing ecosystem health. One of the main objectives of the ReVA program is to identify and prioritize environmental risks likely over the next few decades so that decision-makers can be informed of the trade-offs associated with alternative policy choices (Smith, 2000). Its regional assessment approach may be useful to achieve similar objectives for source water assessment and protection. In addition, ORD's Landscape Ecology Branch has initiated landscape-scale research into evaluating environmental effects of land use on regional scales, and evaluating cumulative effects of multiple stressors. One such evaluation was performed on the impacts on landscape and water resources in the Catskill/Delaware watershed in New York. This study evaluates how temporal and spatial changes in landscape pattern, influence hydrology by increasing water flow, temperature, chemical makeup and benthic structure of the local rivers, streams and creeks.

Research Needs

As exemplified by the citations above and Appendix B, the breadth and depth of technical research on many of the topics directly bearing on source water susceptibility is almost limitless. In fact, these topics practically define entire sub-disciplines of the physical sciences and, consequently, a number of professional journals are devoted to them. There is also a wide range of literature available describing source water susceptibility and sensitivity assessment methods.

However, as noted above, research on the interaction of ground water and surface water is limited, with the exception of studies of GWUDI. Because this interaction varies both spatially and temporally, and is highly dependent on local controlling factors, it is very difficult to generalize ground water/surface water interaction across regions and over time. Additional research is needed on a framework for quantifying the relationship between ground water and surface water in particular geographic settings. This would have benefit for improving the accuracy of susceptibility determinations and setting TMDLs.

While further refinement of our understanding of source water hydrology/hydrogeology and contaminant fate and transport is certainly necessary, the most pressing research needs lie elsewhere. This is partly true because the sub-disciplines devoted to these research efforts will continue to drive investigation independent of regulatory and resource management needs. But more importantly, there is a good understanding of source water hydrogeology, as well as fate and transport of the major contaminant groups, to construct reasonable vulnerability assessment methodologies for a region or locality. At times, it seems that whether we can adequately characterize the susceptibility of a given source water to a particular contaminant is a question of our willingness and ability to commit the necessary level of effort and financial resources.

To date, each state has developed its own approach for susceptibility determinations and most of these approaches are not comparable. As such, regulatory agencies and resource managers may need to focus research in the following areas: (1) investigating ways to **compare the accuracy**

and cost-effectiveness of the various state susceptibility determination methods (both intra- and inter-system methods); (2) developing a set of generic, yet comparable, methods that could be used consistently for **area-wide assessments of specific geologic and geographic settings** (i.e., applicable to multiple systems, multiple jurisdictions, or regions); and (3) developing **methodologies for constructing confidence bounds for susceptibility assessment** results. The ability to quantify confidence bounds for assessment results may aid appropriate agencies and resource managers in choosing a susceptibility assessment method with a resolution appropriate to the level of protection required and the available financial resources. A sensitivity analysis of the impact of various parameters on the water supply's susceptibility would allow decision-makers to prioritize data collection and monitoring efforts.

3. Preventive Measures Against Various Sources of Contamination

Once potential contamination sources are identified and the water supply's susceptibility to each is determined, water system managers and local decision-makers should adopt preventive measures to protect public health from the identified threats. BMPs are methods that have been determined to be the most effective, practical means of preventing or reducing pollution. BMPs can be structural or non-structural measures (see box). Most of the research performed to date relates to structural BMPs, as is presented in the sections that follow.

> ***Structural BMPs***: engineered (i.e., man-made) systems or devices designed to prevent contamination or reduce contaminant loads to source waters from various contamination sources. Examples include containment berms and buffer strips.
>
> ***Non-structural BMPs:*** actions or practices that can prevent contamination or reduce contaminant loads to source waters from various sources of contamination. Examples include farming techniques, land use controls, and educational programs.

This section presents research related to BMPs in general and research into how best to organize for prevention. Research on BMPs that address individual sources of contamination (e.g., storm water runoff and animal feeding operations), and those that address water quantity issues (e.g., water conservation and aquifer recharge) is presented in the sections that follow.

There are a wide variety of potential sources of contamination for which BMPs exist. Resource constraints limit this paper to thirteen source categories, selected for outreach materials development by an advisory group of EPA, state, and association staff. The advisory group selected these categories as the most prevalent, likely to be found in source water protection areas, affecting the largest populations, or with the greatest potential impacts on water sources. Other contamination sources that, while not addressed here, may contribute to drinking water contamination and therefore be worthy of research include: landfills; household hazardous wastes; vehicle servicing facilities; highways; roadway de-icing; construction; and oil, chemical, and waste water pipelines.

Research Question

For all sources, what criteria should be used to determine the effectiveness of BMPs?

> ***Research Needs...***
>
> ✔ BMP selection tools.
> ✔ Performance of BMPs as installed.
> ✔ Consistent methods for comparing and evaluating BMPs.

State of the Science

A large variety of BMPs have been developed to address the many sources of contamination, such as agricultural application of pesticides and fertilizers and underground storage tanks, that could affect water supplies. The most effective management programs combine various BMPs to address all of the significant actual and potential contamination sources present in a water supply's source water area.

A lot of information has been published over the past few decades on available BMPs; their optimal design specifications; effectiveness; and appropriateness to various sources, contaminants, and environments. The bulk of available BMP research relates to their performance in removing or curtailing various contaminants from runoff.

No single BMP can address all actual and potential contamination sources. Each technique or device has limitations based on the hydrology and hydrogeology of the drainage area served, available land space, cost, specific contaminant targeted, and pollutant removal efficiency. Careful consideration of these factors is necessary to select the appropriate BMP or group of BMPs for a particular location (EPA, 1999).

Complicating the BMP selection process is the fact that generally there is a lack of quantitative comparison of the effectiveness of different BMPs on various contaminants (e.g., across multiple BMPs on a single contaminant, a single BMP across multiple regions, and across multiple contaminants using a single BMP). BMP testing is usually performed on a site-specific basis, and given all the variables that can affect performance of BMPs, results often cannot be generalized and applied to different situations or locations (Koustas, 2000).

Comparing and cross-evaluating BMPs and making informed decisions is a difficult and complicated task. This is especially true for decision-makers and planners who may be uninitiated on management measures or BMP technology.

Studies of BMP selection have been more anecdotal than those of the effectiveness or cost of individual measures. For example, many case studies have documented individual communities' experiences in selecting and implementing BMPs. Given that each community has unique situations and pressures, whether they are related to characteristics of the water system, physical properties of the water supply area, identified threats, or political or financial constraints, no one-size-fits-all approach can address every need.

Recently, EPA and other organizations have begun to develop tools to assist managers in making these decisions. Several research initiatives are targeted toward developing tools to aid the selection process.

- *The WATER, Soil, and Hydro_Environmental Decision Support System (WATERSHEDSS).* Developed by North Carolina State University, WATERSHEDSS is computer-based decision support tool to help watershed managers screen storm water runoff control methods. It was designed to assess and evaluate sources, impacts, and management options for controlling nonpoint source pollution in a watershed.

- *BMP Selector.* The [Texas] Statewide Storm Water Quality Task Force has developed an interactive BMP selector to help decision-makers search available BMPs suitable for use in industrial, mixed use, or construction applications. This tool is included in the Texas Nonpoint SourceBOOK (www.txnpsbook.org) on storm water BMPs.

- *National Storm Water Best Management Practices Database.* In a project funded by EPA's Office of Water, the American Society of Civil Engineers (ASCE), and WERF collected existing information on the effectiveness of structural and non-structural BMPs and pollution prevention measures. Available information is summarized in the database, which is available on the Internet at www.bmpdatabase.org and on CD. Additionally, ASCE evaluated cost/benefit information on source and treatment controls to assist the BMP selection process.

Ongoing Research

The Urban Watershed Management Branch (UWMB) of ORD has identified needs for user-assistance tools among its research priorities. Two studies sponsored or funded by UWMB will address evaluations of BMP effectiveness.

- Determination of an optimal method to measure the effectiveness of the most commonly-used BMPs, taking in the account BMP construction issues, operation and maintenance considerations, and test methods.

- Verification testing of wet weather flow (WWF) pollution-abatement technologies to promote new environmentally beneficial technologies by EPA's Environmental Technology Verification (ETV) program. The program will focus on WWF source-area-control devices designed to control or treat storm water as or before it enters the sewer system, and advanced high-rate WWF treatment technologies.

Research Needs

Because the selection of BMPs should be made to address the most significant threats, research is needed into developing tools to help managers properly evaluate and select the most appropriate BMPs to address these threats. A first step, given the great number of combinations of BMPs, contaminant(s), water quality goals, and costs, could be a fairly simple assessment of a current and future **BMP "market" of available tools** and the potential for their use.

Research should address the **performance of BMPs as installed** (e.g., how BMPs were sited and designed) in relationship to the watershed. The ideal BMP installed in the wrong location would not maximize protective benefits and waste precious resources. Research should account for the effectiveness of BMPs in various situations and conditions.

Guidance and strategies are needed on analyzing problems and to developing solutions. These guidances and strategies should take into account the properties of the source watershed, BMP applications, and the feasibility of a BMP approach to removing sufficient runoff pollution to maintain reservoir heath and drinking water safety.

Research into **a consistent way to evaluate and compare BMP effectiveness is needed**. In any decision management tool developed, consideration should be given to what information, such as source water sampling techniques, source water protection results, effluent measurements, loading measurements, or design and maintenance costs, is needed to select the best BMP for their situation.

Other research gaps include:

- Research into methods for evaluating BMPs for contamination sources other than storm water runoff may be needed where storm water research is not directly applicable to these other contamination sources. Some of the research described in this document begins to address these needs; however, most of the BMPs are evaluated under the conditions associated with storm water runoff.

- Apart from evaluating the efficiency of various BMPs, it may also be desirable to assess the hidden environmental costs and benefits of implementing some of these BMPs.

Research Question

What is the best way to organize localities to get the maximum prevention for key threats?

Research Needs...

✔ Optimal structures of watershed groups implementing prevention measures.

State of the Science

Successful prevention efforts that require the consensus and understanding of people with a variety of interests, backgrounds, and knowledge have been a mainstay of promoting these efforts since wellhead protection programs were first established. Without a set of common goals and an organizational team to guide it, no protective effort will succeed. Many models have been developed for the ideal composition of planning groups for communities or groups of communities of various sizes and with differing needs.

Most of the literature on organizing for prevention exists in the form of case studies of communities that have organized community leaders, elected officials, and representatives of the business and agricultural communities to implement wellhead or source water protection programs. They describe the importance of local partnerships and some have highlighted how neighboring jurisdictions have worked together to protect water resources that extend beyond community boundaries. (This research is not described in detail in this paper. A few examples are presented in Appendix B.) See also the discussion of inter-system assessments and area-wide assessments in the susceptibility determination section (Section 2.C).

Ongoing Research

The Environmental Finance Center Network (EFCN) is working to leverage resources to develop unified source water protection plans for clusters of communities in seven states (Colorado, Idaho, New Mexico, North Carolina, Oregon, Texas, and West Virginia). The pilot projects are bringing together drinking water systems that share a common source water with other land use authorities at the federal, state, and local levels to collaborate on developing and implementing source water protection measures. This approach has the potential for greater collaboration in source water protection efforts and may permit communities to achieve greater control measures in protecting their drinking water from contamination. Selected EFCN projects include:

- In Oregon, an EFCN Pilot Project focuses on the South Fork of the Santiam River, which is shared by three communities. In addition to source water protection, the communities are engaged in TMDL compliance and Endangered Species Act issues, and the pilot project will provide insight into the interaction of different federal environmental programs on a common resource. The planning group will consist of non-elected officials from the communities of Sweet Home, Lebanon, and Albany; the South Santiam Watershed Council; Linn County; the Oregon Department of Forestry; U.S. Forest Service; Bureau of Land Management; and the U.S. Army Corps of Engineers.

- In North Carolina, communities that rely on the Broad River and the Second Broad River for their drinking water, including the towns of Forest City, Spindale, Rutherfordton, Ellenboro, Bostic, Ruth, and the Town of Lake Lure, are coordinating on source water protection implementation. The planning effort is under the direction of a local steering committee that, with the input of technical advisors and stakeholders, will review information on threats, prepare a plan to minimize these threats, and seek resources to implement the source water protection plan.

- In the Big Wood River Valley in Idaho, several drinking water systems share a common ground water resource. The EFC is working with the group on financial matters related to plan development and implementation. Blaine County, the first to begin developing a county protection plan, committed $18,000 to assist in developing a countywide source water protection plan. The county will hire a consultant to work with the source water protection group and will develop options for monitoring locations in the county.

- In Berkeley County, West Virginia, state and local officials are concerned about the impacts of rapid population growth, increasing water demands, and land use changes on ground water resources. A Drinking Water Task Force of community and municipal stakeholders within Berkeley County and in surrounding jurisdictions, will convene to develop and implement a unified source water protection plan. Other participants on the effort include Berkeley County, Martinsburg, the federal government (specifically USGS), the State Bureau of Health, Berkeley County drinking water systems, and non-governmental organizations.

Research Needs

A great deal of research into the optimal composition of wellhead protection and source water protection teams has been performed to date. The EFCN is continuing this effort in its source water demonstration projects (described above). Most of this research appears to be community- or area-specific. Given the uniqueness and diversity of the hydrogeology, identified threats, economics, politics, and other factors that can contribute to or impede success, it may be difficult to extrapolate individual lessons learned to a national model.

The potential players in a management effort are diverse, and all should be involved in SWP to some extent. The research need at hand relates to how these players should be organized (e.g., as a watershed group; WHP teams; or groups of elected officials, business leaders, environmental groups, or citizen's groups). That is, what if any, is the optimal way to group these people or localities to realize the maximum prevention for key threats? Also, how do team players work together?

This research into **how to structure alternative watershed groups** to get source water protection done could be assessed in one of three ways. First, we could look at successful and unsuccessful efforts by communities of similar size, demographics, and situations, examine their experiences and outcomes, and compare across cases. A second approach would be to set up and conduct demonstration projects to compare outcomes. A third approach is to assess water quality or other defining measures of success or failure in one or more locality before and after management measures are implemented to attempt to associate team organization with outcomes.

3.A. BMPs to Address Storm Water Runoff

Research Question

What are the cost and performance considerations for storm water BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...

- ✔ Effectiveness of storm water BMPs in various situations or climates.
- ✔ Evaluation of low-cost storm water BMPs.
- ✔ Improved oil-grit separators suitable for small impervious areas, e.g., parking lots.

State of the Science

Storm water runoff is a potential water quality concern in nearly every part of the nation. Not only does storm water carry a wide range of contaminants, including pathogens, nitrates, heavy metals, and organic compounds that can wind up in both ground water and surface water, it can contribute to increased sedimentation and erosion. As awareness of the potential problems associated with storm water increased, many structural and non-structural BMPs have been developed to address this concern.

Structural storm water BMPs include devices and systems that slow or retain runoff to allow contaminant removal, such as vegetative measures (e.g., buffer strips and filter strips), ponds and constructed wetlands. Other structural devices encourage sedimentation and oil and grease removal, such as oil-grit separators. These measures can be applied in urban, suburban, or rural areas. Some of these measures are also used to address other contamination sources (e.g., animal wastes); studies of these applications are discussed in the appropriate sections of this report.

A large volume of information exists on storm water BMPs. Most of these studies relate the effectiveness of the BMP in reducing contaminant loads in different land uses or climates. A sampling of available studies is described below and listed in Appendix B.

Several studies assess the effectiveness of *buffer strips* planted with various vegetation types and with differing designs. Dillaha et al. (1989), Magette et al. (1987), Schwer and Clausen (1989), Doyle et al. (1977), Barker and Young (1984), and Overman and Schanze (1985) studied the effectiveness of grassed buffer strips of varying widths, reporting removal rates for solids and nutrients. Lowrance et al. (1983 and 1984) studied phosphorus removal efficiencies by native hardwoods, and phosphorus and nitrogen removals in forested buffers. SMRC (2000b) describes various factors (such as slope grade, runoff velocity, depth to water table) that can enhance the performance of buffer strips.

Yu et al. (1992) investigated pollutant removal efficiencies of grassed *filter strips* near a large parking lot. Removals of total suspended solids (TSS), nitrogen, total phosphorus, and extractable lead and zinc were assessed for filter strips of varying widths. In agricultural settings, Desbonette et al., (1994) reported removal rates for nitrogen, phosphorous and sediment by filter strips.

Rates of TSS, phosphorus, nitrogen, nitrogen, and metals removal by several types of *wetlands,* including shallow marshes, detention wetlands, pond/wetland systems, and submerged gravel wetlands have been studied. For example, Godrej, et al. (1999) studied the performance of a constructed wetland in the Washington, DC area, representing a non-arid urban environment in removing ammonia, nitrate, and TSS.

Erosion and sedimentation control (ESC) measures, such as sediment traps and basins, sediment fences, and wind erosion controls can mitigate the erosion and sedimentation caused by storm water runoff at construction sites. The Construction Engineering Research Foundation, Environmental Technology Evaluation Center (EvTEC) tested the performance of several ESC measures, including blown straw for slope treatments, hay bale checks, and the Tommy Silt Fence Machine, a device which inserts silt fence without displacing the soil. This testing was completed in 2000 and the results are under EPA review.

Oil-grit separators (OGSs) remove hydrocarbons or excess sediment, either alone or in combination with vegetative measures to pre-treat runoff. Studies of removal of solids, nutrients, and polycyclic aromatic hydrocarbons by OGSs have been performed in Washington, D.C., Wisconsin, Washington, and Alberta, Canada. One study suggests, however, that OGSs are not suitable for small areas, such as gas stations or small parking lots.

Non-structural measures to control storm water runoff include land use controls and low impact development. The Chesapeake Research Consortium (1998) compared the nutrient export and economic benefits of conventional and innovative site planning techniques in the Chesapeake Bay watershed. Various development scenarios wereassessed for differences in the amount of impervious cover, runoff and infiltration volumes, cost, and nitrogen and phosphorus output between conventional and innovative site design.

BMPs for *Class V storm water drainage wells* address siting (e.g., minimum setbacks from surface water, wells, or areas of critical concern); design (including pretreatment devices such as infiltration trenches, wetlands, and oil/grit separators to eliminate pollutants from storm water before they reach the well); and operation (e.g., spill response, monitoring, and maintenance) of these wells. Several studies of the effectiveness of design BMPs that may be used in the vicinity of Class V storm water drainage wells are described above.

Ongoing Research

Ongoing research related to storm water runoff is aimed at identifying cost-effective BMPs, assessing the performance of BMPs for urban areas, and on reducing the impacts of construction.

To address the need for cost-effective BMP technologies, EvTEC and the University of Arkansas plan to evaluate low-cost storm water BMP technologies (i.e., under $3,000) to address first flush storm water. The specific technologies to be studied have not been selected.

EvTEC is also working with the Washington State Department of Transportation on field verifications of innovative commercial stormwater BMPs to manage urban storm water runoff. They include: (1) BaySaver's Treatment System, which separates oil, grease, debris, and sediment from storm water in a dual-tank system; (2) the StormVault system (developed by Jensen Precast) which catches oil, grease, and sediment; and (3) the Aqua-Filter by Aquashield Inc., which combines a swirl concentrator pretreatment followed by a filtration chamber to remove soluble and insoluble pollutants at high flow rates. In other urban storm water research funded by WERF, Kieser is reviewing an urban drain improvement project in Michigan to develop storm water BMPs for cold water habitats.

USGS is evaluating the effectiveness of plastic silt fences and hay bales, especially as they are affected by physical site and rainfall characteristics, for upland and hilly terrain of Alabama and the Southeast.

Research Needs

Research on some storm water BMPs presents a wide range of removal efficiencies for certain contaminants, (e.g., phosphorus removals ranging from 8 to 88 percent by buffer strips). A synthesis of the understanding of **which BMPs are most effective in various situations or**

climates (e.g., urban areas, cold weather, or high rainfall) would be useful to managers as they plan to manage source water areas.

Given that BMP selection may be a low priority for land owners who are unfamiliar with their importance, low-cost alternatives may be preferred. Continued **studies of low-cost BMPs**, similar to EvTEC's (described under ongoing research) would provide useful information to support the BMP selection process.

Research indicates that OGSs are not suitable for small impervious areas, such as gas stations or fast food store parking lots. Given the pervasiveness of these establishments, additional research into **optimizing the performance of OGSs in small impervious areas** is needed.

Other research gaps include:

- Research is also needed on how measures can be used or combined to maximize removal of the most contaminants at the lowest cost. Given the wide variety of establishments where storm water controls are needed, an understanding of the effectiveness in specific situations and to certain contaminants (as well as communicating the appropriateness of these measures to land owners), along with cost-effectiveness evaluations, are needed to maximize the use of storm water BMPs.

- Other avenues for further research include thermal effects and nutrients in storm water runoff.

- Research into appropriate placement of BMPs, BMP scaling, and BMP data and procedures for watershed modeling is needed as well.

3.B. BMPs to Address Septic Systems

Research Question

What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters from septic systems?

Research Needs...

✔ Optimal design and BMPs for septic systems in various climates and topography.
✔ Alternatives to traditional septic systems.
✔ Presence and impacts of endocrine disruptors in septic system wastes.

State of the Science

Also known as onsite or decentralized waste disposal systems, septic systems have the potential to introduce a variety of contaminants, including pathogens, pharmaceuticals, and nutrients, into ground water, and may impair surface water as well. Management is important due to the high number of septic systems that exist, many serving single-family homes. Systems with the capacity to serve more than 20 persons a day are Class V injection wells and are subject to federal requirements of non-endangerment to underground sources of drinking water (USDWs).

Non-structural BMPs for septic systems address siting, operation, and maintenance. Many local health departments have passed ordinances to protect ground water from private septic systems, including siting requirements such as horizontal and vertical setbacks, adequate soil permeability, design and construction requirements related to drain field size, and specifications for appropriate soil characteristics and topography. Operation and maintenance considerations include inspections, sludge pumping, and water conservation. Structural BMPs include the installation of grease interceptors, denitrification systems, sand filters, and constructed wetlands.

Research on septic systems has focused on the effectiveness of structural measures, reduction of nitrogen contamination, and reduction of pathogen and microorganism contamination of ground water. Many studies on the effectiveness of constructed wetlands in treating waste water have been conducted (Bastien and Hammer, 1993; Bastien et al., 1989; Corbitt and Bowen, 1994; Hammer, 1989; Moshiri, 1993; Weider et al., 1989). More recently, EPA (2000) published a set of fact sheets describing other structural measures. Research has also addressed techniques to reduce nitrogen contributions to ground water through non-structural and structural management practices. A 1991 study by Wall presented the best management practices to reduce nitrogen contamination, and EPA published a bibliography of research in 1992. The prevention of contamination by microorganisms and pathogens was studied by Yates in 1987 and 1989.

Research has also focused on general management issues with decentralized systems, and projects have been conducted in a few states. The National Onsite Wastewater Recycling Association held a conference addressing issues in on-site waste water treatment in Wisconsin in 1994. A revised model of management practices was presented at the conference, with the belief that it could eventually be implemented nationwide.

Ongoing Research

EPA is proposing voluntary national guidelines for the management of decentralized waste water systems. These guidelines aim to help communities meet water quality and public health goals, as well as offer a wide range of cost-effective options for meeting waste water needs. Representatives of private industry are also investigating new technologies to address these same concerns. In addition, two organizations, the Consortium of Institutes for Decentralized Wastewater Treatment and the Texas Onsite Wastewater Treatment Research Council, are supporting further research efforts regarding onsite waste water treatment through grants and contracts.

EPA is developing the Onsite/Decentralized Wastewater Systems Program Strategy, which presents the Agency's vision and mission towards improved performance of onsite/decentralized systems. The strategy discusses ways EPA can work to eliminate barriers to implementing successful onsite waste water systems. Among the research and data gathering initiatives EPA plans are:

- To address public misperceptions about decentralized systems, EPA will facilitate research needed to improve credibility and acceptance of their use. EPA will also provide assistance in upgrading State training and certification programs for practitioners (e.g., designers, installers, inspectors, and maintenance providers).

- To resolve problems related to legislative barriers and regulatory constraints, EPA is supporting demonstrations in performance-based management programs, and the National Onsite Wastewater Recycling Association (NOWRA) National Model Performance Code.

- Few communities have the necessary organizational structures to effectively manage or identify the onsite/decentralized systems within their jurisdiction, failures associated with these systems, and maintenance required. EPA will analyze options for collecting information to better characterize the nature of these problems and will continue to fund demonstration projects and conduct outreach to assist with implementation of improved state and local management programs.

Research Needs

Research may be needed to identify **which available BMPs for septic systems are cost-effective to install and operate**, especially in various climates or topography. This may be especially important in efforts to promote adoption of septic system BMPs beyond those specified in health department regulations for homeowners and small businesses that operate septic systems. If owners of these systems understood that specific measures would be the most beneficial to their community, especially based on assessment results, they may be more receptive to adopt them.

Research should also address development of feasible **alternatives to traditional septic systems**, particularly in source water protection areas and in reducing the number of septic systems. Potential technologies include composting systems, wetland treatment systems, and bioreactors.

The **presence of endocrine disruptors**, such as organochlorine compounds and pharmaceutical steroids, in domestic wastes, and their health effects on humans and the environment has become a concern in recent years. Research may also be needed to assess the impacts of these substances in septic system wastes and whether BMPs and treatment in place is adequately addressing them.

3.C. BMPs to Address Above-Ground Storage Tanks

Research Question

What are the cost and performance considerations for BMPs for above-ground storage tanks to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...	
✔	ASTs that can withstand severe weather, earthquakes, and collisions.
✔	Low-cost leak-detection equipment for ASTs.

State of the Science

Spills from above-ground storage tanks (ASTs) can contaminate nearby surface and ground water supplies with petroleum and other hazardous chemicals. Large-capacity oil-storage ASTs are Federally regulated by EPA under the Oil Pollution Prevention Rule at 40 CFR Part 112, also called the Spill Prevention Control and Countermeasures (SPCC) Rule. The Rule was designed to prevent spills into surface waters, and to set procedural and technical spill control requirements for ASTs.

Required structural BMPs to address above-ground storage tanks include secondary containment such as berms, dikes, liners, vaults, and double-walled tanks. Corrosion protection measures include elevating tanks off the ground, double-walled or lined tanks, and cathodic protection.

Various studies have been published on the effectiveness of structural measures. The American Petroleum Institute (API) published reports evaluating the effectiveness of leak detection methodologies, tank field dike lining materials, and the cost-effectiveness of retrofitting tanks with release prevention measures. The effectiveness of cathodic protection systems in preventing corrosion in steel tanks was studied by the National Association of Corrosion Engineers. EPA conducted a study on the environmental- and cost-effectiveness of tank liners, and in its *Compliance Assistance Guides* series, summarized specific BMP technologies and their limitations. API also published a report linking the effectiveness of diked-area liner systems with environmental quality impacts.

Non-structural measures include required routine monitoring, leak detection audits, and inspections. The effectiveness of non-structural measures in reducing or preventing contaminant releases from ASTs has also been studied. EPA looked at the impact of SPCC regulations on environmental quality in 1995. Analysis of a national survey of oil storage facilities indicated that compliance with the SPCC requirements "reduced both the number and volume of spills, as well as the amount of oil migrating outside of the facility's boundaries." The study also noted that tank leak detection, spill overfill protection, pipe external protection, and secondary containment, also appear to reduce the number and magnitude of oil spills.

Ongoing Research

EPA hosted the Fourth Biennial Freshwater Spills Symposium in March of 2002. The symposium addressed problems of freshwater oil spills, and one of the planned topics for discussion was tanks and standards.

Research Needs

The BMPs available to address ASTs have been well studied; in addition the SPCC requirements appear to be effective in addressing and mitigating the common avenues for discharge of contaminants. However, **unexpected events, such as inclement weather, earthquakes, and even accidental collision** may result in the catastrophic failure of above-ground storage tanks. The commonly used BMPs do not appear to be effective in addressing these situations. More studies are needed on how to better plan for and protect tanks from these kinds of dangers.

Development of **low-cost leak detection equipment** that requires minimal maintenance and operator training should also be researched.

3.D. BMPs to Address Underground Storage Tanks

Research Question

What are the cost and performance considerations for BMPs for underground storage tanks to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...

- ✔ Reliable UST leak-detection technologies.
- ✔ UST designs for earthquake-prone areas.

State of the Science

Many states report that their leading source of ground water contamination is leaking underground storage tanks (USTs), and, at one time, EPA estimated that almost 25 percent of underground storage tanks in the U.S. were leaking. The majority of USTs contain petroleum products, and leaking tanks can introduce benzene and other carcinogens into USDWs. EPA regulates USTs under Subtitle I of the Resource Conservation and Recovery Act (RCRA), which sets operating requirements and technical standards for USTs.

Required structural BMPs include spill and overfill protection devices, corrosion protection such as construction with noncorrodible material, cathodic protection, double-walls, or tank lining, and leak detection devices such as automatic tank gauging, interstitial monitoring, inventory reconciliation, vapor monitoring, and ground water monitoring.

Recent research has focused on the development and evaluation of leak detection technologies. In 2001, the National Work Group on Leak Detection Evaluations compiled the 9th edition of their report. Intended as a reference manual, the *List of Leak Detection Evaluations for Underground Storage Tank Systems* summarizes independent evaluations of leak detection technologies.

Specific structural measures have also been addressed in recent research. API has published several reports evaluating technologies such as the cathodic protection of tanks, and interior lining of tanks. No studies were identified that directly link improved BMP effectiveness and water quality improvement.

Ongoing Research

EvTEC, a division of ASCE, is currently evaluating the *Low Range Differential Pressure (LRDP)* leak detection technology. The system is designed to detect small leaks in bulk (large-capacity) USTs, and is being tested in several large-scale demonstrations in Hawaii and California.

Research Needs

Leak detection technologies appear to be the focus of most of the recent research on UST BMPs. Development of **low-cost leak detection equipment** that requires minimal maintenance and operator training should continue to be the focus of research. Research into alternatives to heating oil for schools or small water systems may eliminate the need for some USTs or encourage their replacement.

Underground storage tanks are susceptible to **failure during earthquakes**. More engineering studies are needed on how to better design or site tanks in earthquake-prone areas.

Other research gaps include:

- In 1998, some 370,000 leaking UST sites were being monitored by EPA. More studies are needed on how to cost-effectively clean up these sites and upgrade tanks to eliminate the risk of source water contamination, and so that they are compliant with Federal regulations.

3.E. BMPs to Address Vehicle Washing Facility Wastes

Research Question

What are the cost and performance considerations for BMPs for vehicle washing facilities to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...
✔ Studies of BMP effectiveness specific to vehicle wash wastes.

State of the Science

Vehicle washing occurs at commercial car wash facilities, public works garages, car dealerships, truck stops, and many other types of facilities. Wash water can flow into storm drains and enter surface water sources untreated, percolate to ground water through the soil, or enter the subsurface through Class V carwash wells. Vehicle wash water contains oil, grease, metal (paint chips), phosphates, detergents, soaps, cleaners, road salts, and other chemicals that can contaminate source water.

Structural devices for the proper management of vehicle washing waste water include oil/water separators, sediment traps, recycling systems, or runoff control devices such as grassed swales or constructed wetlands.

Most of the research performed on these structural measures is related to storm water runoff in general, and not specific to the runoff near car washes. Many of the contaminants likely to be found in car wash water are also in storm water and have been studied. Therefore, research on storm water would also apply to vehicle washing facilities.

Research on oil and grease removal in storm water runoff has been documented in several studies in the National Storm Water Best Management Practices Database. Studies assessed oil and grease removal by dry detention basins in Michigan, Texas, and Washington; by wetlands in California and Oregon; and by swales in Virginia and Washington.

EPA (2000) states that, based on the limited data available, most storm water BMPs demonstrate high hydrocarbon removal efficiencies. Ponds, wetlands, and filters exhibited median removal rates of 80 to 90 percent. Swales demonstrated hydrocarbon removal rates of 62 percent. These methods all demonstrated similar removal efficiencies for solids.

There are three basic types of oil-water separators–spill control, API Separator (longer retaining time), and coalescing plate separator (Oregon DEQ, 1998). Studies of removal of solids, nutrients, and polycyclic aromatic hydrocarbons by oil-grit separators have been performed in the District of Columbia, Virginia, Washington, Wisconsin, and Alberta, Canada.

Recycling systems reduce or eliminate contaminated discharges to storm water drains and injection wells by reusing the wash water. These systems can treat and reclaim 100 percent of their captured waste water (USEPA, 1992).

These measures may be used in combination to allow removal of the various types of contaminants in waste waters. For example, oil-water separators may remove oil and grease, and be coupled with a vegetative measure that can filter detergents and road salt. Horner et al. (1985) studied the combined performance of a detention basin and coalescing plate oil separator.

BMPs for Class V carwash wells involve treatment of wash water by the methods described above to remove pollution before it reaches the well.

Ongoing Research

No current research on BMPs for vehicle wash wastes was identified.

Research Needs

As noted above, while much research into the effectiveness of many of the structural measures (such as vegetative filters and oil-grit separators) used to filter or remove the pollutants in carwash waste water, none appears to be directly related to waste water generated at *these facilities* in particular. Studies of the **effectiveness of BMPs in removing contaminants specific to vehicle wash wastes** is needed.

Other research gaps include:

- Research may be needed to identify which of the available BMPs are most effective and least expensive to install and operate at vehicle washing operations to prevent contaminant discharges or minimize the geographic spread of contaminants to source waters. However, given the wealth of existing storm water research, this may a lower research priority.

3.F. BMPs to Address Small Quantity Chemical Use, Storage, and Disposal

Research Question

What are the cost and performance considerations for BMPs that could be implemented at facilities that use, store, and dispose of small quantities of chemicals in order to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...

✔ Expanded research on innovative technologies for Small Quantity Generators (SQGs), e.g., wet-cleaning.
✔ Low-cost BMP selection tools for Small Quantity Generators.

State of the Science

Dry cleaners, laundries, printers, vehicle maintenance or repair shops, and medical facilities are among the many types of establishments that use a wide variety of chemicals in their daily operations and produce chemical waste. The pervasiveness of these facilities and the toxic nature of some of the chemicals they use make them a potentially significant threat to water quality. (Note: BMPs for users of large quantities of chemicals are not addressed in this research paper. These facilities are usually subject to industry-specific requirements.)

Many BMPs and pollution prevention techniques are available for use at the large number and variety of establishments that use chemicals. These BMPs focus on reducing water or chemical use; recycling or recovering waste water and waste chemicals; and using alternative, less toxic substances. While much has been written on encouraging the use of these measures and the resultant cost savings, there is less information is available on their effectiveness and no assessments of how widely they are used or accepted.

Reducing water consumption can bring about substantial savings on water costs, which may be one of the larger monthly expenditures for some small businesses. For example, research on laundry facilities has focused on developing washing machines that reduce water consumption. Medical facilities have many options for reducing water use in laundries, for food preparation, and in restroom facilities.

By reducing the use of toxic chemicals, operators can save the cost of over-purchasing these expensive chemicals, lower waste disposal fees, and provide safer workplaces. For example, research has been completed on the use of dry wash or CO_2-based dry cleaning technologies, which do not produce hazardous wastes or use toxic chemicals. One such recent advance is a sophisticated machine-based process called "wet cleaning" which uses water, rather than perchloroethylene, as the solvent (EPA, 1998). An EPA-sponsored wet cleaning demonstration project in Chicago, IL will be used to educate the dry cleaning industry about wet cleaning alternatives and encourage the use of non-toxic alternatives.

Recovering and recycling chemicals keeps them from the environment and reduces chemical and disposal costs. Research on BMPs for dry cleaning operations focuses on the recovery of VOCs, for example, by using systems that do not require manual transfer of treated material between cleaning units. Recycling process water may save water costs and reduce the amount of pollutants leaving the facility. A technology to collect, filter, and recycle screen solution at silk screen printing facilities has also been developed. This recycling system collects the water for reuse by removing the emulsion, allowing the rinse water to be reused for approximately one month (T.S. Designs, 1997).

Facility operators can switch to less toxic chemicals that perform the same functions as chemicals typically used. For printing facilities, the Printwise lithographic ink and water-based presswash printing system is designed to reduce emissions of VOCs by employing a vegetable oil-based ink that reacts with the presswash to become water-soluble. The University of Tennessee evaluated alternatives for degreasing automotive parts, including aqueous washing and a hot water wash system. At medical facilities, measures are implemented to address reducing use of mercury and pharmaceuticals. The Minnesota Center of Environmental Advocacy has been working with Minnesota health care providers to purchase less environmentally harmful products. Automotive repair shops can switch to less toxic paints and recycle solvents; one small repair shop reduced liability and saved $4,800 annually in waste management costs (Washington DOE, 1995).

Some of the types of facilities described above may have Class V wells. Research related to BMPs for Class V wells is presented in Section 3.L.

Ongoing Research

Green chemistry involves the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. The principles of green chemistry include: designing synthetic chemicals to maximize the incorporation of all materials used into the final product, use and generation of substances that possess little or no toxicity, design for degradation, and selection of substances to minimize the potential for chemical accidents. This approach to pollution prevention is the focus of research by EPA's Green Chemistry Program, the National Environmental Technology Institute, and the Green Chemistry Institute.

Under EPA's Green Chemistry Program, the Small Business Innovation Research (SBIR) Program provides financial support to help small science- and technology-based firms develop environmental technologies and ready them for the market. The program targets research to prevent and reduce pollution, and manage solid and hazardous wastes.

To date, the National Environmental Technology Institute (NETI) has funded 39 projects in pollution prevention research. Current projects in FY 2002 address development of specialized polymers and recycling of waste polyesters.

The Green Chemistry Institute (GCI) works across disciplines and academic, government, and industry sectors to promote the development and implementation of science and technology to prevent generation and production of hazardous wastes. GCI awards Green Chemistry research fellowships for chemical and engineering thesis work to promote scientific research.

Research Needs

There are a large number of BMP and pollution prevention measures available to businesses that use and generate small quantities of chemicals. Source water protection planners need to be able to effectively communicate to business owners about BMPs and encourage their adoption. This effort would be aided with the development of tools for decision-makers to use in determining which BMPs are appropriate to the sources identified in their assessments and understanding the use and effectiveness of BMPs.

Several **innovative technologies** are described in the scientific literature. These methods, such as wet-cleaning, reduced water laundries, and low-toxicity paints, should be evaluated and developed where necessary to bring effective, **low-cost BMP technologies** into the financial reach of small business owners.

3.G. BMPs to Address Animal Waste

Research Question

What are the cost and performance considerations for BMPs for animal feeding operations to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

Research Needs...

✔ Ability of BMPs to remove hormones and antibiotics from animal waste.
✔ BMPs for controlling poultry wastes.
✔ Expanded research on biodrying, composting, and storage of manure in earthen confinements or lagoons.

State of the Science

Animal feeding operations (AFOs) are of concern because the manure generated at these facilities is a potentially significant source of pathogens, including *E. coli, Cryptosporidium, Giardia lamblia,* and *Salmonella*, all of which can cause serious acute health effects. Nitrates, antibiotics, hormones, and various metals may also be present in animal waste. Considering the large numbers of AFOs across the nation, the potential for widespread contamination is significant.

Animal feeding operations and other nonpoint sources of pollution have been a focus of study and review by SDWA and CWA programs for years. Pathogen transport and proliferation can be controlled by reducing the transport of animal waste from the AFOs into the environment, managing animal wastes within AFOs, and controlling the proliferation of pathogens within AFOs.

Structural BMPs for use at AFOs include several types of vegetative measures that can filter pathogens and other contaminants associated with animal wastes to prevent them from entering sources of drinking water. Other techniques are designed to retain or transform the fecal waste, reducing the potential for contamination from runoff. Many studies of these techniques are available; a sample are described below, and more are presented in Appendix B.

Buffer zones/filter strips are effective in removing animal waste and have been examined in studies specific to various animal wastes and conditions. These studies include vegetative filters for beef and dairy runoff (e.g., Sanderson et al., 2001) and for swine manure (e.g., Hawkins et al., 1998). Poultry litter and filter strips were the subjects of studies by Edwards et al. (1997) and Chaubey et al. (1995). Several studies address contaminant removal through series of *riparian buffer* zones (Hubbard et al., 1993, 1995, and 1999; USDI / BLM, 1998). Srivastava et al. (1996) studied the impact of the size of a *filter strip* in removing pollutants. Edwards et al. (1996) and others demonstrated that buffer strips improve the quality of runoff from land treated with manure. The effectiveness of vegetative *filter strips* to reduce feedlot runoff was examined in several studies, including Young et al. (1980). In lab conditions, Coyne et al. (1998 and 1995) concluded that fecal bacteria and coliforms were trapped by grass filter strips.

Constructed wetlands are the subject of studies of their ability to remove pathogens. For example, one study concluded that constructed wetlands have demonstrated removal efficiencies of 82 to 100 percent for fecal coliforms (Hammer, 1989). Research addressed the effectiveness of constructed wetlands for treatment of dairy effluent (Cooper et al., 1994; Zimmerman et al., 1994; and others); swine waste water (including Rice et al., 1998; Payne et al., 1992); combined dairy and swine waste water treatment (Cronk, 1996); and poultry lagoon waste (Hill et al., 1996). A few studies have examined constructed wetlands in specific geographic settings, for example, Borer et al. (1996) examined constructed wetlands in the Southern U.S., while Pries et al. (1996) examined them in the Northern U.S.

Waste that cannot be land-applied is held in a *treatment lagoon,* where pathogens are reduced through biological, physical, and chemical processes. Studies on the effectiveness of treatment lagoons for swine and dairy waste were conducted by Cheng et al. (1999), Schneider (1990), and many others. The effectiveness of an anaerobic lagoon was examined by Safley and Westerman (1992) and Harmon and Privette (1991). Swine lagoon seepage was examined by Westerman et al. (1995).

Waste storage is also an important BMP. To create the most effective storage facility, a number of factors are considered. In a study by Barrington et al. (1995), organic liners are tested for their ability to prevent seepage. Earthen storage facilities were studied by Nibbling and Falk (1997), Barrington and Broughton (1988), Miller et al. (1985), and Rowsell et al. (1985).

Composting is an effective management technique to reduce pathogen concentrations, as the consistently hot temperatures prevent most organisms from surviving. The effectiveness of composting is the subject of many evaluations, including DeLuca and DeLuca (1997) and St. Jean (1997). Separated swine manure composting was studied by Liao (1993), while Richard (1998) focused on high-moisture manures. *Biodrying* maintains manure in its solid form, reducing the risk of spillage. Wright (2000) studied the effectiveness of biodrying dairy manure.

Nonstructural BMPs used at animal feeding operations include land application of manure, herd management, and grazing practices. Studies of *land application of manure* attempt to identify the optimal timing, environment, and conditions to reduce potential runoff. For example, timing animal waste application during dry weather conditions would prevent microorganisms from being carried by rainwater and entering the source water. The effectiveness of land application of manure has been widely examined. More studies of the effectiveness of manure application are presented in Section 3.H.

Herd management includes segregating animals, maintaining clean facilities, and maintaining the general health of the herd to reduce the incidence of disease and control the proliferation of pathogens. Grazing management studies were conducted by Mathews et al. (1994) and Moore (1988). Many studies address grazing management and the placement and distribution of manure and its effect on streambanks and streams. A variety of studies also investigated the effectiveness of stream fencing to prevent pollution from grazing animals.

Combining BMPs can be an effective approach to ensure the greatest possible removal of contaminants at AFOs. Several studies evaluate the effectiveness of combining BMPs for addressing dairy and beef waste (including Baldwin, 1997; and Heatwole et al., 1990); poultry waste (Chapman, 1996); and swine waste (e.g., Edwards and Daniel, 1993; Sutton et al., 1987).

While pathogens pose the greatest health concern, nutrient removal is important as well, and several studies examine the effectiveness of BMPs in addressing nutrients. BMPs for nitrogen management were conducted by Dou et al. (1996), Holloway et al. (1996), and Kanwar et al. (1995). BMPs to manage phosphorus from entering drinking water sources were investigated by Weaver and Ritchie (1994), Meals (1993), Mahler et al. (1992), and Robillard and Walter (1986). Integrated BMPs for nutrient management include examinations of a grazing environment by Shreve et al. (1996), and Schmidt and Wolfley (1992); and the combination of filter strips and tillage is the subject of a study by Madison et al. (1992).

Several recent technologies have been developed to improve the aforementioned BMPs. Manure separation technologies are described by Chastain et al. (1998). Another possible measure to reduce phosphorus pollution by poultry litter is the addition of an enzyme to feed (Sohail and Roland, 1999; University of Delaware, 1999; and Edens and Simons, 1998). Alternative waste management technologies were also investigated by Hannawald (1999), Dalsted et al. (1997), and Master (1993). A study by Keener et al. (1999) evaluated the design and management of a swine manure drying facility.

Economic considerations are as important as the BMP itself. If a BMP is not cost-effective, it is unlikely to be widely used, regardless of its effectiveness. Economic investigations for swine and dairy waste management were conducted by Massey et al. (1998), Fleming and Babcock (1997), and Allen et al. (1991). Cost issues associated with the storage and handling of waste were studied by Hilborn (1996) and Shutske et al. (1993). The economics of manure application were investigated by Harman et al. (1994), and economic issues related to grazing management were covered by Wagstaff (1986).

Ongoing Research

Moore and Donoghue are investigating the long-term impacts of manure management strategies on source water, and developing additional BMPs to reduce phosphorus runoff. In New York State, a recently-completed study evaluated BMPs for minimizing phosphorus losses from farming in a watershed (Gburek et al., 2001). A nutrient management project by Sharpley et al. continued through April 2002 to define BMPs that minimize nutrient transfer from agricultural lands to water sources. Finally, a study by Sheldon et al., which will be completed in 2005, is assessing the effectiveness of vegetative buffer strips, riparian zones, and wetlands on pathogen transport.

Research Needs

There is a great body of scientific research on the availability and effectiveness of structural and nonstructural BMPs in reducing pathogen transport from AFOs. The addition of **hormones and antibiotics to animal feed** and the health effects on humans and other animals that consume the meat products has become a concern in recent years. New research into the effectiveness of existing techniques (or the need for new technologies) in removing these substances from the animal wastes may be needed.

The body of scientific research on animal feeding operations appears to concentrate most heavily on livestock and swine, and less research on available measures for use at poultry operations appears to have been done. Further research into **controlling poultry wastes** may be needed.

Additionally, very few studies have investigated the effectiveness of **biodrying** as a waste management practice. More research could be conducted on **waste storage in earthen confinements** or lagoons. Also, research on the benefits of **composting** as alternative to lagoon storage and prior to spreading on fields is recommended.

3.H. BMPs to Address Fertilizer Application

Research Question

What are the cost and performance considerations for BMPs to prevent or minimize discharges of fertilizers, or minimize the geographic spread of fertilizers to source waters?

Research Needs...

- ✔ Regional research on the effectiveness of specific BMPs for fertilizers, such as crop rotation and filter strips.
- ✔ Precision agriculture technologies, especially the development of low-cost techniques.
- ✔ Research on the effectiveness of BMPs for agricultural drainage wells.
- ✔ Crop management methods to minimize fertilizer needs and releases to runoff.
- ✔ Fertilizer use by and effectiveness of outreach programs to homeowners and non-agricultural users.

State of the Science

Fertilizers, used widely in agricultural operations and by homeowners, are sources of nitrogen, phosphorus and other nutrients, and pathogens, which can contaminate drinking water supplies. Fertilizers can be managed by reducing the potential for nutrients to move into surface or ground water sources through efficient fertilizer use. A variety of structural and nonstructural BMPs exist to address fertilizer use. Much research on the effectiveness of these measures can be found in scientific literature. Described below are several areas in which research has been completed in the last two decades.

Filter strips can impede runoff and allow the filtration of nitrogen and phosphorus. The effectiveness of filter strips on water quality was investigated in many documented studies, including Franti (1997) and Dillaha (1987). The effectiveness of these BMPs also depends on a number of regional factors, as shown by Barfield et al. (1998) who examined filter strips in karst areas. Srivastava et al. (1996) demonstrated that the length of the filter strip can impact its effectiveness. Economic considerations for filter strips are addressed in several studies (Nakao et al., 1999; Pritchard et al., 1993).

Riparian *buffer zones* were the focus of studies by Dosskey et al. (1997) and Gold and Groffman (1995). Nutrient removal by grass and riparian buffers was investigated by Parsons et al. (1994).

Non-structural BMPs to minimize nutrient loss due to fertilizer application include crop rotation and proper rates, timing, and methods of application.

Studies on *crop rotation* by Carpenter-Boggs et al. (1999), Webster and Goulding (1995), and Huang and Uri (1994) focus on nitrogen abatement. The effectiveness of *tillage* on nitrogen and phosphorus runoff has been examined in several studies. Katupitiya et al. (1997) and Kanwar et al. (1991) examined the long-term effects of tillage and crop rotation on ground water. Tillage research was conducted to determine the most effective tillage systems for minimizing phosphorus in runoff (Janssen et al., 1998; Gupta et al., 1997).

Studies on nitrogen, phosphorus, and potassium *fertilizer application* include the effectiveness of variable application rates (Anderson-Cook et al., 1999), and a combination of method, rate, and placement (Gordon, 1998; Sharpley, 1997; Wetselaar, 1974). Koelsch (1997), Barker (1996), and others report on the effectiveness of direct field application of fertilizer derived from animal waste. Additional discussion of livestock waste is presented in Section 3.G.

Nutrients are transported in a dissolved form or attached to soil particles. *Nutrient management programs* address both forms. The effectiveness of nutrient management has been examined by Hall et al. (1997), Koerkle and Gustafson-Minnich (1997), and others. The economics of nutrient management programs were addressed in a report by USDA (USDA/ARS, 2001).

Financial incentives (most notably cost-savings of using less product) are well-documented in several studies, including Wu and Babcock (1998) and Tauer (1988). Huang et al. (2001) and Ribaudo et al. (1999) found that various incentives for farmers to utilize BMPs would, in turn, decrease nitrogen fertilizer use. The decreased need for fertilizers due to crop rotation and tillage has been estimated by Katsvairo and Cox (2000) and Uri (1999), among others.

Class V wells are often present in an agricultural setting. *Agricultural drainage wells* serve as a direct conduit to ground water. BMPs for preventing fertilizer contamination via agricultural drainage wells are described in studies by Kennicker et al. (1998), Mumm and Heathcote (1997), Quade and Seigley (1997), Mohanty et al. (1996), Baker et al. (1995), Leme et al. (1995), IDALS (1994), Tobin et al. (1990), Chescheir et al. (1988), and Kanwar et al. (1986).

Ongoing Research

Precision farming is a relatively new concept which evaluates specific field conditions using technologies such as soil sampling, remote sensing, GIS, and GPS for the purpose of precisely adjusting fertilizer application. USDA-Agricultural Research Service (ARS) is evaluating methods and equipment to deliver fertilizer in the needed amount at the right time to maximize uptake by plants and minimize the potential for movement of fertilizer into the water supply. Several studies have examined precision farming's effectiveness, profitability, and emergence in agricultural research (Lambert and Lowenberg-DeBoer, 2000; Bouma et al., 1999; Torbert, 1999; Weiss, 1997). Testing to determine soil nitrogen levels to prevent over-nitrification has been examined by Franzluebbers et al. (1995). Spray equipment attached to a self-propelled sprinkler irrigation system is being developed and tested to vary the application of fertilizer as needed. Low-cost GPS systems are being adapted to determine its location in the field to allow automated control of both irrigation and fertilizer application.

The USDA/ARS has several studies underway related to fertilizer BMPs. A study that began in the spring of 2001 and is set to be completed in 2006 (Follett et al.) seeks to improve water quality and fertilizer use efficiency, develop cost-effective nutrient management to increase nitrogen use efficiency, determine BMPs to prevent surface or ground water contamination, and develop, test, and/or calibrate nutrient management tools to evaluate nutrient, irrigation, and other BMPs to reduce residual soil nitrate. The South Florida Restoration Science Forum in conjunction with the USGS will investigate phosphorus BMP implementation.

Research Needs

While progress has been made in reducing the need for fertilizers and increasing the efficiency of their application, research gaps remain. Research is needed on both a regional scale, i.e., to determine which technologies work best in various climates and situations, as well as on specific technologies to bolster their usefulness and effectiveness.

More **regional research** is needed on the effectiveness of specific BMPs, such as crop rotation and filter strips, and on nutrient removal in various situations or climate conditions characteristic of different regions of the country. Research into the effectiveness of specific methods, such as **precision agriculture technologies** should continue as well, especially into the development of low-cost techniques.

While a great deal of research has been conducted on the potential harm that **agricultural drainage wells** pose to sources of drinking water, few studies have examined the effectiveness of BMPs associated with them.

Additional research on **crop management methods** or combinations of methods that could minimize both fertilizer and pesticide/herbicide needs or runoff may be needed as well.

Many outreach materials have been written to educate homeowners on the proper use of fertilizer (notably on selecting appropriate fertilizers and reducing the amounts used). However, no research on the **effects of fertilizer use or ways to encourage reduced use** or alternatives to fertilizers **by homeowners** was identified. Given the large number of residential lawns and their potential cumulative effects on water quality, research on fertilizer use and effectiveness of educational and other programs to encourage proper fertilizer use may be warranted.

3.I. BMPs to Address Pesticide and Herbicide Use

Research Question

What are the cost and performance considerations for BMPs to prevent or minimize discharges of pesticides and herbicides, or minimize the geographic spread of pesticides and herbicides to source waters?

Research needs...

- ✔ Effectiveness of pesticide removal by constructed wetlands and grassed buffer areas.
- ✔ Crop management methods to minimize pesticide/herbicide needs and release to runoff.
- ✔ Reducing pesticide and herbicide use by or proper techniques homeowners and non-agricultural users.

State of the Science

Pesticides and herbicides are applied to crops by aerial spraying, topsoil application, soil injection, soil incorporation, or irrigation. Aerial spraying and topsoil application pose the greatest risks for pesticides and herbicides to run off to surface water bodies, and soil injection and incorporation pose the greatest threat of ground water contamination. Pesticides and herbicides contain a variety of organic and inorganic compounds that can endanger human and animal lives. Many of the compounds in these products are difficult and expensive to remove from drinking water supplies.

The application of pesticides and herbicides and the resultant runoff has been the subject of several studies over the past 20 years. Most of the available research relates to agricultural practices, and much less research related to reducing pesticide use by homeowners, on golf courses, and park lands has been performed. Options for homeowners to minimize the need for pesticides and herbicides include integrated pest management, proper pesticide application, reducing pesticide use (i.e., through plant management, manual hoeing, and weeding), and proper pesticide storage and handling. BMPs have evolved to prevent and reduce the presence of pesticides in source waters.

BMPs to address pesticide and herbicide application include various tillage practices, crop rotation, vegetative buffers, tile-outlet terraces, and constructed wetlands.

Conservation tillage can reduce pesticide and herbicide runoff in much the same way it reduces fertilizer runoff. Several studies have demonstrated the effectiveness of tillage systems on pesticides including those by Fawcett et al. (1994), Seta et al. (1993), Smith (1993), Felsot et al. (1990), Berryhill et al. (1989), and Baker and Johnson (1979). Atrazine runoff under various tillage management systems has been studied by Basta et al. (1997) and Anderson and Kazemi (1988). The long-term effect of tillage on herbicide transport was studied by Isensee and Sadeghi (1995). Several studies compared the effectiveness of various tillage systems in removing pesticides (e.g., Masse et al., 1998) and herbicides (including Shipitalo et al., 1997; and Gish et al., 1995).

Crop rotation has not been studied as extensively as conservation tillage, but a study by Shivankar and Kavadia (1992) examined its effects on the persistence of heptachlor. However, crop rotation is a component of an integrated pest management plan, which is explained further below.

Vegetative buffers and strips trap and degrade pesticides and herbicides before they enter source water. Many studies examine the effectiveness of vegetative buffer and filter strips in reducing concentrations of a variety of pesticides and herbicides. Several studies evaluated the use of specific vegetation within the buffer or filter strips to reduce pesticide runoff, including grass and wheat filter strips to reduce herbicide runoff (Hoffman, 1995), switchgrass and cool-season grass (Lee, 1997), and stiff-grass hedge (Meyer et al., 1995). Tingle et al. (1998) and Castel et al. (1994) studied the optimal size and width of a filter strip for maximum pesticide removal.

The effectiveness of *tile-outlet terraces* to reduce herbicide losses is the subject of studies by Franti et al. (1995 and 1998) and Mickelson et al. (1998). Few studies have analyzed the effectiveness of pesticide trapping by *constructed wetlands*; one such study is by Matter (1993).

Non-structural BMPs for pesticides in the agricultural setting address proper application techniques. Several of these application practices were examined by Bode (1990). Studies on the effectiveness of these BMPs generally focus on a particular pesticide. The effectiveness of various pesticide and herbicide application techniques were studied by Huang and Ahrens (1991), Baker and Shiers (1990), Hamilton et al. (1989), and Nicholaichuk and Grover (1983). Grisso et al. (1988) studied the accuracy of pesticide application equipment.

Combining BMPs can maximize the removal of pesticides and herbicides. The efficiency of combination BMPs is the subject of many studies, including Setia and Piper (1992) and Gish et al. (1991) on pesticide reduction, and Christensen et al. (1993) on minimizing herbicide runoff. Other examples include a study by Mielke et al. (1981) on the use of irrigation and tillage on herbicide loss, Kanwar et al. (1991) on the effects of tillage and crop rotation on pesticide loss, and Watts and Hall (1996) on tillage and application effects on herbicide leaching and runoff.

Cost-benefits are implicit in the use of BMPs due to the decreased use of pesticides. An *integrated pest management plan* (IPM) is designed to reduce the use of pesticides through a combination of various means. IPM strategies include, but are not limited to: field scouting for potential problems; pest-resistant crop varieties; crop rotation; improved tillage practices; diversification of habitat; and the timing of planting, irrigating, and harvesting. An economic evaluation of IPM systems was complied by Norton and Muller (1994). Economic impacts of pesticide practices were analyzed by Randhir and Lee (1997), Pimentel et al. (1993), and Sabbath et al. (1992).

Ongoing Research

A USDA-ARS study (Potter et al.) is investigating BMPs that protect ground and surface water from agricultural chemicals. It will be complete in 2003.

An unpublished USGS study (Shaw) investigates the benefits of various BMPs in reducing herbicides in runoff. This project evaluates the effects of a stiff-grass vegetative filter strip in conjunction with conventional and conservation tillage systems on off-site movement of two widely used soil-applied herbicides. Laboratory studies will determine herbicide adsorption and degradation in the filter strips, treated fields, and at various points within a riparian forest in one of the watersheds.

Research Needs

While a great deal of research has been conducted on pesticide and herbicide removal, research into some specific methods could be expanded. For example, few studies have evaluated the effectiveness of **pesticide trapping by constructed wetlands**. Also, while several studies have investigated the effectiveness of vegetative filter strips in general, there are few studies on **specific grasses in buffer areas to help reduce and trap pesticides**. As noted above, there also appears to be less research on the **effectiveness of crop rotation** as a means to reduce pesticide and herbicide pollution.

As stated above, no research related to **reducing pesticide and herbicide use by homeowners or on commercial spaces such** as golf courses, retail establishments and office parks, cemeteries, and park lands has been identified. Given the large number of these establishments and their potential cumulative effects on water quality, research on reducing pesticide and herbicide use or proper techniques may be warranted.

Other research gaps include:

- Additional research on crop management methods or combinations of methods that could minimize both pesticide/herbicide and fertilizer needs or runoff may be needed.

- A large amount of research exists on pest-specific and crop-specific integrated pest management methods. A catalog or searchable data base of these methods would improve access to and understanding of available methods.

3.J. BMPs to Address Combined and Sanitary Sewer Overflows

Research Question

What are the cost and performance considerations for BMPs for combined and sanitary sewer overflows to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters?

> ***Research Needs...***
>
> ✔ Emerging technologies related to treating Combined Sewer Overflows (CSOs) and Sanitary Sewer Overflows (SSOs).

State of the Science

Combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) are discharges of untreated sewage that can lead to source water contamination. The untreated sewage can be discharged directly into basements of homes, streets, parks, and surface waters. They can threaten drinking water supplies by carrying bacteria, viruses, and protozoa directly into source water and can cause property damage as well.

Structural controls to improve sewer systems involve upgrading collection systems (e.g., using PVC pipes instead of those constructed with concrete or metal), constructing wet weather storage facilities such as overflow retention basins, or building a new sewer collection system.

Jason Consultants International (2000) identified and evaluated new and alternative materials and techniques for use in sewer systems and considered design developments and implications that have arisen from these new materials and methods.

Bennett et al. (1999) provided waste water utility managers and consultants with tools to select appropriate rainfall-derived infiltration and inflow (RDII) flow projection methodologies to help control sanitary sewer overflows and wet weather flows in general.

Recent research into improving SSO technologies includes the following:

- In 1995, the Fairfax County (Virginia) Wastewater Collection Division (WCD) began using a capacity, management, operation and maintenance (CMOM) approach to abate SSOs, extend the life of its sewer system assets, and improve customer satisfaction. Since its inception, WCD's CMOM program has cut SSOs by 67 percent, reduced operations and maintenance and capital improvement costs, and led to a major restructuring of WCD's personnel organization.

- In 1986, Oklahoma City implemented a program to replace one percent of its sewer lines each year. Oklahoma City is replacing the sewer lines with PVC pipe; it is affordable, flexible and corrosion-resistant. Over the past 14 years, Oklahoma City has decreased the number of emergency SSO calls from hundreds per year to just 23 in 2000.

CSO control technologies include a number of engineering methods such as deep tunnel storage, in-system control/in-line storage, off-line near-surface storage/sedimentation, vortex technologies, and disinfection. Recent CSO research includes the following:

- Moffa and Associates (2001) developed protocols to evaluate treatment and control technologies and associated benefits to receiving waters. The report includes six case studies of CSOs, storm water, and agricultural runoff.

- Boner et al. (1994) investigated the degree of contaminant removal by a modified vortex separator (MVS), a CSO control device using dissolved air flotation, ultraviolet (UV) disinfection, and/or chemical addition. The study presents pollutant removal data for total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), fecal coliform, and phosphorus. Due to a failure of the system, results are preliminary only; however, the MVS may be useful as a high-rate, efficient CSO treatment.

Ongoing Research

EPA initiated the Environmental Technology Verification Program Wet Weather Flow Technologies Pilot in 1998. EPA is developing a program to conduct credible and objective verification testing of fully-developed and commercially available urban WWF abatement systems. Two types of WWF systems will be verified in this pilot: (1) WWF storm-inlet devices that are designed to control/treat storm water as it enters the sewer system, and (2) advanced high-rate WWF treatment technologies that belong to four general groups: sedimentation, micro- and fine-mesh screening, biological, and disinfection processes.

The Louisville and Jefferson County (Kentucky) Metropolitan Sewer District (MSD) recently conducted a full-scale demonstration project of deflective separation, a technology that has applications in storm water liquid-solids separation. The project will collect test data from the MSD facility to evaluate the effectiveness of the technology in CSO treatment. This project is one of the first CSO applications of deflective separation technology.

In 1995, the Ohio River Valley Water Sanitation Commission (ORSANCO) initiated a multi-year wet weather study in the Cincinnati/Northern Kentucky area. The study involves intensive sampling of the river under both dry and wet weather conditions. Results of this sampling will be used to develop a model of the study area that can be used to evaluate alternative controls of wet weather pollution sources.

In a project sponsored by WERF, Brashear is assessing the effectiveness of existing and emerging technologies for CSO and SSO treatment. This research will enable users to select the best wet weather treatment process for a particular situation.

Research Needs

Several ongoing research initiatives are examining **emerging technologies related to treating CSOs and SSOs** to reduce contamination of source water. These research activities should continue.

3.K. BMPs to Address Biosolids Application

Research Question

What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters due to biosolids application?

Research Needs...

✔ Impacts of pharmaceuticals and other chemicals in biosolids.
✔ Research on which biosolids measures are the most effective in various regions of the country.

State of the Science

The land application of biosolids, or treated sewage sludge, occurs in all 50 states. Biosolids may contain metals and pathogens, and must meet standards for use as a fertilizer or soil conditioner. In 1993, EPA promulgated 40 CFR part 503, which set limits on pollutants and requirements for land application, surface disposal, and pathogen and vector reduction, and general provisions for management practices for biosolids application. Biosolids that meet these standards are considered safe for land application when BMPs are followed.

BMPs for biosolids deal with aspects of transport, storage, and land application. Non-structural measures include agronomic load rates, soil conservation practices, field slope limitations, odor control, proper application rates, proper storage and handling, and harvest, grazing, and crop restrictions. Structural BMPs include buffer zones to filter contaminants from runoff that flows over applied biosolids. The effectiveness of these BMPs for nutrient and pathogen removal has been studied extensively. Many of these studies are described in the section on application of fertilizers (see Section 3.H).

Research on the effectiveness of BMPs for biosolids application has been conducted primarily through the USDA, WERF, and universities, as part of water quality or soil science programs. WERF has funded projects on biosolids application, including a project assessing the development, status, and cost effectiveness of different management technologies. The USDA compiled a report that focuses on the uses of biosolids and other organic wastes, and discusses research needs and management practices for land application of biosolids (Wright et al., 1998). EPA studied BMPs for the treatment, transport, and storage of biosolids prior to land application (USEPA, 2000).

Ongoing Research

EPA is funding 20 National Monitoring Program projects intended to determine the most effective BMPs for preventing nonpoint source pollution. Most of these projects are still in the implementation stage. Other projects funded by WERF focus on developing or assessing requirements and improving safety for biosolids. One such project is attempting to develop national guidelines for designing and implementing a biosolids management program. Additional research addresses identifying and assessing requirements for human parasites and other biocriteria in municipal biosolids.

Research Needs

Quite a bit of research has been performed on the effectiveness of vegetative measures, such as wetlands, in removing nutrients and pathogens, especially related to agricultural fertilizer application. Some of this research is specific to applied biosolids, and EPA and WERF are adding to the current body of knowledge in this area.

As noted in the discussions of septic systems above (Section 3.B), the **presence of pharmaceuticals and antibiotics in domestic waste water** is being recognized as an emerging threat. Research on biosolids should evaluate whether these substances are present in biosolids, and whether management measures exist and can effectively address them.

Research that can identify **which of the available measures are most effective in various regions of the country** would be valuable to decision-makers. Other questions that may need to be answered include the degree to which these practices improve water quality, and how feasible and cost efficient each measure is. Additional research that could better educate the public on the benefits (and risks) of biosolids application would be useful as well.

3.L. BMPs for Injection Wells

Research Question

What are the cost and performance considerations for BMPs to prevent or minimize discharges of contaminants, or minimize the geographic spread of contaminants to source waters due to injection wells?

Research Needs...
✔ Continued research on Class V injection wells.
✔ Alternatives to discharging to floor drains.

State of the Science

EPA's UIC Program, established by the 1974 SDWA, oversees the injection of fluids below the surface.[1] Requirements for injection wells are set forth at 40 CFR parts 144 through 148. Deep injection wells have sophisticated multi-layer construction with redundant safety features. Throughout their operational lifetimes, these deep injection wells are operated, monitored, and inspected regularly to verify proper operational conditions and that the well components are structurally secure. Ambient ground water monitoring may be required as well. When injection operations are complete, wells are closed in a manner that is protective of USDWs.

Recent research initiatives by EPA and others have focused on Class I deep injection wells and Class V wells.

Deep wells, especially Class I wells, are the most stringently regulated injection wells and their inventories and locations are well known. These wells have been subject to the most study as well. For some injection wells, especially Classes I, II, and III, specific BMPs are required and set forth in regulations. Much research has been performed on various aspects of the siting, construction and performance of deep injection wells. Topics of study include well design and construction, ground water monitoring, containment of hazardous wastes, the appropriateness of some wastes for injection, models of waste movement, risks posed by injection wells, and the effects of injection in the subsurface.

EPA recently completed a study for Congress on the risks associated with Class I injection wells (EPA, 2001). This study reviewed several aspects of injection well technology, including design

[1] The Act defines five classes of wells. Class I wells inject hazardous/non-hazardous industrial and municipal waste water beneath the lowermost USDW. Class II wells are used to dispose of fluids brought to the surface in connection with oil or natural gas production, to inject fluids for enhanced recovery of oil or natural gas, or to store hydrocarbons. Class III wells inject fluids for the extraction of minerals. Class IV wells inject hazardous or radioactive waste into or above strata that contain a USDW (these wells are banned). Class V includes wells not included in the other classes; examples are agricultural drainage wells, storm water drainage wells, and industrial drainage wells.

and operational requirements, and concluded that the measures in place at these wells are sufficient to protect human health and the environment.

Less is known of the number and location of Class V wells. EPA believes there are over 650,000 of these wells; however, many are un-inventoried and their exact number and location area unknown. While the composition of the waste water discharged through Class V wells is unknown, most are believed to pose a lesser threat than the deeper well types due to the types of wastes discharged. Class V wells are associated with a large variety of industrial, agricultural, and other activities. As such, they can potentially contribute a wide range of contaminants with chronic and acute health effects, including pathogens and nitrates, hazardous materials, sediments, and industrial wastes, some of which may be expensive to remove from drinking water.

In 1999, EPA conducted a comprehensive national study of Class V wells that included a review of available BMPs for all types of Class V wells, including their effectiveness (EPA, 1999). BMPs for Class V wells may include vegetative measures to treat runoff before it enters the well or design standards to prevent contamination of ground water. Other sections of this research plan discuss BMPs for specific Class V well types, including storm water drainage wells (Section 3.A), septic systems (Section 3.B), carwash wells (Section 3.E), agricultural drainage wells (Section 3.H), and aquifer recharge and storage and recovery wells (Section 3.O).

Ongoing Research

EPA is conducting a study of possible impacts of hydraulic fracturing of coalbed methane wells may have on underground sources of drinking water. The Agency is gathering information on the hydraulic fracturing process and requesting public input on contamination allegedly due to hydraulic fracturing practices. EPA will use the results of this effort to determine whether additional research on CBM wells is required.

In its ongoing Class V initiative, EPA continues to review regulatory and non-regulatory approaches for managing industrial waste disposal wells, storm water and agricultural drainage wells, large-capacity septic and on-site waste water disposal systems.

Research Needs

In general, it is believed that BMPs for deeper wells, especially Class I wells, are sufficient to protect the environment from the waste waters injected into these wells. Operators of these wells are highly qualified and selection and construction of management measures is closely supervised by EPA and state UIC programs.

For Class V wells, the same research needs discussed in other sections of this report may be relevant. Operators of these wells likely need assistance in understanding which BMPs are most effective in various situations. A synthesis of available **information or other decision support tools may be useful to Class V well operators** and source water planners. EPA continues to research the wastes discharged to these wells, along with options for addressing unacceptable threats. Additional research needs may arise from this effort.

It may also be useful to examine and promote various methods available as **alternatives to discharging into floor drains**, such as absorbent materials to soak up spills or holding tanks. This may also promote pollution prevention at small quantity chemical use, storage, and disposal facilities (see Section 3.F). See also the discussion of containment methods for contaminant response in Section 4.B.

3.M. BMPs to Address Abandoned Wells

Research Question

What are the cost and performance considerations for methods to prevent contamination of source water due to the presence of abandoned wells in water supply areas?

> ***Research Needs...***
>
> ✔ Technical assistance on properly interpreting available geophysical data on abandoned wells.
> ✔ Tools to link and display new and historical land use and contaminant source data for locating abandoned wells.

State of the Science

Abandoned wells can be direct conduits from the surface to ground water, carrying contaminants directly to the water table. Abandoned drinking water wells are a particular concern, as they tap directly into USDWs. Abandoned wells are also a safety hazard, because people or animals can fall into them and be injured or trapped by them.

Managing abandoned wells requires locating and properly sealing them. Once found, abandoned well should be sealed, usually per local regulations. This section focuses on technologies for locating abandoned wells.

Abandoned wells may be found by searching for indicators of their presence, such as pumps, pipes protruding from the ground, or surface depressions. Reviews of historical photographs, maps, land ownership records, and building and water rights permits may also help identify the locations of older wells. State departments of health have data on abandoned water wells, and state oil and gas commissions are sources of oil and gas well information.

The materials of which wells are constructed may produce geophysical anomalies. Recently, geophysical methods have been applied to locating underground objects, including abandoned wells. These include magnetic, electromagnetic, and acoustical surveys.

Steel-walled abandoned wells can be located through ground or airborne magnetic surveys using metal detectors or magnetometers. A high-resolution aeromagnetic survey near the Glen Hummel oil field in Texas identified magnetic anomalies of natural and man-made origin. Correlation of the anomalies with state data demonstrated that aeromagnetic surveys are effective in locating abandoned wells (Wilson et al., 1997). The USGS conducts and interprets such surveys on request (USGS, 1995) and airborne magnetic survey data is available from NOAA.

The Kansas Geological Survey conducted electromagnetic (EM) surveys at varying frequencies in Hutchinson, Kansas using the GEM-2 electromagnetic sensor. The survey successfully located one uncapped abandoned brine well 5 feet deep, demonstrating that EM surveys are successful and effective in locating abandoned wells (Xia, 2001b).

The University of Wyoming investigated the use of acoustical techniques to determine the status of plugged and abandoned wells by estimating the size and location of plugs, which reflect acoustical signals. In a test of seven wells, the best results were seen on an unplugged water well. Although acoustic records from plugged wells have been more challenging to interpret, this technique, if successful, could be used to determine which abandoned wells require mitigation (Kubichekl et al., 1997).

Aerial photography and satellite imagery may be used to locate abandoned wells. These images could reveal physical structures, surface disturbances, or stressed vegetation (due to contaminated ground water or lowered water tables) that may indicate the presence of abandoned wells below. The National Aeronautics and Space Administration (NASA), USGS, and the Natural Resources and Conservation Service can provide aerial photographs of varying scales.

Once located, the position of the abandoned (and, ideally, plugged) well can be plotted on a map or pinpointed using a GPS for input into a GIS. This information can support updates to source inventories (see Section 2.B).

Ongoing Research

The U.S. Minerals Management Service is studying the use of satellite radar imagery to detect leaking abandoned wells. In this two-phase investigation, the methodology will be tested in Phase I, and a pilot test of the method may take place in the Gulf of Mexico Region. (Note: the MMS web site is currently off-line - no additional information on the project is available.)

No other ongoing research on the use of geophysical methods to locate abandoned wells was identified; however, the application of these techniques continues as part of the source inventory phase of source water assessments.

Research Needs

As stated above, much imagery and geophysical data is available from government agencies. However, technical expertise is needed to properly interpret the data. For example, satellite images are typically available in digital format and require trained personnel to accurately interpret them. Research can be conducted to **develop automated procedures to assist decision-makers** in using them.

Decision-makers need effective **tools to link new and historical data** and display the results in a meaningful way (e.g., in a GIS). This research priority strongly relates to those for source inventories described in Section 2.B.

3.N. BMPs Involving Water Conservation, Reuse, and Recycling

Research Question

How can water conservation, reuse, and recycling minimize contamination or the geographic spread of contaminants to source waters?

> ***Research Needs...***
>
> ✔ Linking conservation and reuse/recycling programs to water quality improvements.
> ✔ Potential negative water quality impacts of reduced waste water flows.
> ✔ Effective conservation methods for reducing water use and maintaining water quality for various land uses.

State of the Science

Excessive water use can contribute to the degradation of source waters by increasing the mobility of contaminants present. Heavy ground water withdrawals can increase the movement of a plume of contaminants or, in the case of coastal aquifers, induce saltwater intrusion (McPherson and Halley, 1996; Renken, 1998). Excessive watering of agricultural or residential land potentially increases the amount of polluted runoff. Additionally, excessive pumping may increase the vulnerability of ground water sources to contamination because it can expand the area of the aquifer contributing to a water supply, or can alter ground water flow patterns (see Section 2.C on susceptibility determinations for a more complete discussion). Water reuse, recycling, and conservation can mitigate these negative effects on source water by decreasing water demand.

Water reuse programs employ municipal waste water (gray water) or reclaimed water for an alternative "beneficial" use such as agricultural irrigation. Additional potential applications include industrial uses, landscape irrigation, and fire protection (USEPA, 1992). Water recycling is the reuse of water for the same application, such as cooling water recirculation and wash water recycling in industrial plants (OAS, 1997).

The effectiveness of water reuse programs have been addressed generally in recent research. An assessment of the costs and benefits of reuse alternatives was examined by Crook and Bastien in 1992, who expanded on EPA Guidelines for Water Reuse (EPA, 1992). The American Water Works Association (AWWA) and WERF published a joint report outlining reuse of water. The economic feasibility of water reuse was studied in Florida by Elsner (1993). Another study discussed reasons why water reuse had not been implemented in many municipalities (Arber, 1991).

BMPs for water conservation address engineering practices such as plumbing, fixtures, and operating procedures. These include low-flush toilets, pressure-reduction devices, and low-volume irrigation devices. Low-flush toilets and other devices for saving water have been widely implemented, especially in drought-susceptible states and communities. Their effectiveness is well documented as well—reductions of residential water use from 20 to 40 percent have been demonstrated (OAS, 1997; Pearson, 1993).

The effectiveness of agricultural and landscaping water conservation measures in reducing surface and ground water contamination has been studied extensively. Specific studies have also addressed the effectiveness of low-volume irrigation devices, and non-structural measures such as conservation tillage. In addition, the effectiveness of irrigation scheduling in water conservation has been studied (Bosch and Ross, 1990). EPA published a report in 1993 on the effectiveness of xeriscaping practices on preventing pollution and saving water. See also Section 3.H on BMPs for application of fertilizers for agricultural uses.

Non-structural BMPs include pricing, irrigation scheduling, and educational programs. The effectiveness of pricing and rate adjusting in water conservation has also been studied. A USGS study examined farmer response to water conservation pricing to determine which programs are most effective in reducing water demand (Michelson, 1998). Other studies have analyzed the effectiveness of pricing and rate adjustment programs in cities across the U.S. (Cuthbert, 1989; Martin and Kulakowski, 1991).

The effectiveness of various BMPs for conserving water has been addressed extensively as part of management plans or general conservation studies. In his report, *Water Reuse in the United States*, J. Crook (1992) discussed the effectiveness of water saving techniques, including agriculture or landscaping irrigation, industrial uses such as cooling or boiler process waters, recreational uses and habitat restoration or enhancement. The Organization of American States studied water conservation practices, including the effectiveness of various structural and non-structural technologies (OAS, 1997). The Federal Energy Management Program, within the Department of Energy (DOE), which helps implement conservation practices that include water conservation in federally managed operations, published a report discussing structural and non-structural BMPs and their effectiveness.

Ongoing Research

USGS is conducting several studies of the effects of water conservation (or lack thereof), and reuse practices on source water quality. One study is investigating the impacts of Florida water management practices on saltwater intrusion of surficial aquifers. A similar project is studying how the implementation of conservation practices, and specifically reuse, can ensure the Chipuxet aquifer in Rhode Island contains adequate water supplies for users by decreasing water demand. USGS is also funding a study investigating minimizing ground water contamination potential when applying reclaimed water to agricultural land for irrigation. Another USGS-sponsored project will assess the feasibility of using gray water for lawn irrigation.

Research Needs

As noted above, the effectiveness and acceptance of water conservation techniques and programs are well-documented. The effects of excessive water withdrawals in "stressing" aquifers and taxing water systems are understood as well. However, other than for agricultural practices, no studies directly linking the installation of water saving devices and reuse/recycling programs to water quality improvements were identified.

USGS is beginning to study the **linkage of conservation and water quality**. The results of this research could be quite useful to decision-makers in bolstering adoption and acceptance of conservation efforts. Research should also assess the **potential negative impacts of reduced waste water flows**. Water conservation/recycling could have some unintended consequences of water quality degradation if flow to streams is reduced significantly.

Additional research that identifies **which conservation methods are most effective** in reducing use and maintaining water quality for various land uses or customer bases (e.g., residential vs. commercial) could benefit the development of SWP programs.

3.O. BMPs Involving Aquifer Recharge, Aquifer Storage and Recovery, and Aquifer Remediation

Research Question

How can aquifer recharge, aquifer storage and recovery, and aquifer remediation minimize contamination or the geographic spread of contaminants to source waters?

Research Needs...

- ✔ Research on how storage and recharge operations affect water quality.
- ✔ Disinfection by-product formation in finished water reservoirs and aquifers.

State of the Science

The injection of water into surficial aquifers is conducted for three main reasons: to store water for future use, to recharge depleted (stressed) aquifers, and prevent saltwater and other contaminant intrusion, and to perform in-situ remediation or to restrict contaminant movement. Treated or untreated surface or ground water may be injected into an aquifer. Chemicals, microorganisms, and other remediation agents may also be injected.

Aquifer recharge, aquifer storage and recovery (ASR), and aquifer remediation wells are classified as Class V wells. In 1999, EPA conducted a comprehensive national study of Class V wells that included a review of the effectiveness of BMPs for these well types. BMPs that are applicable to these wells address recharge water quality, water monitoring, and aquifer clogging (USEPA, 1999).

The effectiveness of water quality monitoring as a control on aquifer clogging and recharge quality has been addressed in the High Plains Aquifer Study being conducted in the Midwest (Shea-Albin, 1997), and as part of the Equus Beds Ground Water Recharge Demonstration

Project begun in 1995 (Ziegler et al., 1999; 1997). An AWWARF study evaluated well clogging relationships, and developed a model for predicting the fate of contaminants during storage. The reduction of aquifer clogging as a result of interaction between recharge and native water has also been studied (Pitt and Magenheimer, 1997; Van Beek, 1986).

In addition, the effectiveness of recharge, recovery, storage, and remediation in decreasing source water degradation has been studied.

Aquifer Recharge, Storage, and Recovery

The effectiveness of recharge as a means to decrease contamination in an aquifer has been studied (Ma and Spaulding, 1997; Pinholster, 1995; Pyne, 1996). An AWWARF project also evaluated whether disinfection by-product concentration reduction occurs during ASR storage, and assessed the probable causes. Other studies document water quality improvements associated with surface recharge as water moves though soils (Bouwer, 1991). Studies have modeled the use of aquifer storage to capture wet weather flows for use during dry periods (Vivoni, 2000).

Aquifer Remediation

Recent research has focused on the development and effectiveness of innovative technologies for remediation of contaminants in aquifers, including multi-well systems, pump-and-treat systems, steam injection, air sparging, and horizontal wells. In addition, extensive research has been conducted on the development and effectiveness of injecting various chemical and biological remediation agents.

Ongoing Research

Ongoing research of aquifer recharge addresses the effects of water use practices, water quality improvements during recharge and storage, and the feasibility of recharge as a method to meet future water-supply needs. The High Plains Regional Ground Water Study is studying the effects of land- and water- use practices on ground water resources and the feasibility of artificial ground water recharge. Other ongoing projects include pilot projects in Merced, California, and the Eastern Snake River Plain, Idaho, that are investigating the feasibility of managed ground water recharge of an aquifer. The Equus Beds Ground Water Recharge Demonstration Project will investigate artificial recharge and its benefits for future water supply needs and prevention of saltwater intrusion (Ziegler et al., 1999). AWWARF is also studying water quality changes associated with recharge and ASR. One study taking place in California is analyzing water quality changes as water moves from artificial recharge sources to drinking water wells. The second study is analyzing water quality improvements during ASR storage.

Ongoing research on aquifer remediation is focused on developing new technologies and approaches to improve water quality. The Federal Remediation Technologies Roundtable is an inter-governmental agency group working to identify cost-effective solutions to hazardous waste remediation studies. Studies are examining in-situ ground water treatment and pump and treat technologies.

Research Needs

There is a high interest in aquifer remediation technologies and, as a result, this topic is well-funded and heavily researched.

Research needs for recharge and ASR wells are similar to those for water conservation techniques, which are also aimed at increasing available water supplies. Research into **how storage and recharge operations affect water quality** could improve the acceptance of these measures. Research on aquifer storage should also address **disinfection by-product formation** in finished water stored in reservoirs and aquifers.

4. Effective Contingency Planning

Contaminants may be introduced into source water by accident (resulting either from a failure of protective measures at facilities or from a natural disaster), or deliberately (through an act of sabotage or a terrorist attack). In a report issued by its Risk Science Institute (RSI), the International Life Sciences Institute (ILSI, 1999) noted that drinking water utility managers perceive the most significant threats to be: (1) spills of oil and industrial products from tanks, pipelines, or transportation; (2) insecticides and herbicides from agricultural runoff; and (3) pathogens from untreated sewage discharges. Intentional threats or sabotage against water supply systems have until recently been considered relatively small, and include (1) destruction of parts of a system by either computer hacking or physical destruction; or (2) contamination of the system with chemicals, microbes, toxins, or radioactive compounds (ILSI, 1999).

The goals of an effective contingency plan are to detect, delay, and defend against contaminants that are introduced to the source water of a drinking water supply and/or to minimize the health impacts resulting from a contamination event. This section describes recent and ongoing research into methods to detect and contain various types of contaminants. Regional models of early warning monitoring systems are also addressed.

4.A. Detection Methodologies

In the event that contaminants enter source waters–whether accidentally or deliberately–it is important that an effective system be in place to detect their presence as quickly as possible. The more lead time water suppliers are given of a threatening situation, the better chance they have to address the threat without disrupting the delivery of safe, clean drinking water. Given that removing some contaminants requires expensive, sophisticated technologies, early detection has the potential to significantly reduce treatment costs.

Research Question

What are the most efficient and effective methods for monitoring for various contaminants introduced accidentally or deliberately to source waters?

Research Needs...

- ✔ Real-time or near real-time pathogen and virus detection.
- ✔ Promising technologies for detecting chemical (including emerging contaminants) and radiological contaminants.
- ✔ Time of travel to surface water intakes.
- ✔ Testing and application of early warning chemical monitoring technologies.

State of the Science

An effective detection method would reliably, quickly, and accurately detect the presence of contaminants in source water introduced through accidents or deliberate sabotage. There are a variety of physical detection and laboratory analytical methods available for detecting pathogens, organic and inorganic compounds, and radioactive compounds in either ground or surface water supplies.

Microbials/Pathogens

Research on technologies for pathogen monitoring are concentrated in two main areas: (1) developing methods that provide accurate and rapid or real-time results; and (2) developing methods for detecting pathogens that have been identified as possible or probable bioterrorism agents. Researchers generally recommend that the ideal microbial monitoring methods be rapid, providing results in two hours or less. Traditional microbial detection methods rely on microbial amplification, which is very time-consuming. Two approaches have been developed which bypass this step. The first uses a detectable marker to amplify cell signals electronically. The second approach amplifies the DNA or RNA of a cell using molecular techniques, such as polymerase chain reactions. Ideal methods should also be quantitative or semiquantitative and measure multiple organisms simultaneously, with on-line capability for continuous monitoring in a variety of applications, including surface water, ground water, and distribution systems (ILSI, 1999).

AWWARF is a valuable source of information on real-time analytical methods for the detection of contaminants. Some studies have focused on the health effects of contamination and have investigated the viability and infectivity of the pathogens of concern. *Cryptosporidium, Giardia,* and *E. coli* strains have been researched the most. Recent research has identified many potential biological or bioterrorism agents such as *Shigella, Vibrio cholerae, Salmonella* species, hepatitis A virus, and *Cryptosporidium parvum* that could threaten drinking water systems (Burrows and Renner, 1998; Craun, 1992; Levy et al., 1998). Also, *Bacillus anthracis, Brucella, Francisella tularensis,* and *Yersinia pestis*, which cause anthrax, brucellosis, tularemia, and plague have generally been considered as biological warfare agents and are stable in water.

Moe (1999) identified several new approaches for rapid monitoring of microbes in water supplies. DNA microchip arrays are a recently developed technology that allows detection and identification of multiple organisms within four hours. Immunomagnetic separation with solid-phase laser scanning cytometry is another method for rapid separation and detection of microbes. Flow cytometers have reportedly also been used to detect bacteria, molds, and yeast in less than 30 minutes. In-depth descriptions of these methods are provided on-line and may be found in Appendix B.

Available systems for rapid detection of biological and chemical contamination were addressed at the Water Security Summit, held in December 2001 in Hartford, CT. Systems highlighted at the Summit include both on-line systems and laboratory or field instruments: continuous adenosine triphosphate (ATP) analyzer, immunomagnetic separation, Microtox system, R.A.P.I.D. (used by the military), BAX System (polymerase chain reaction-yielding DNA analysis), RiboPrinter (a laboratory instrument), flow cytometry, Eclox-M (chemoluminescence-based), and fish- and daphnid-based real-time toxicity sensors.

Bacterial Source Tracking (BST), also known as fecal source tracking and/or fecal typing, is a new methodology for determining the sources of fecal bacteria in environmental samples (e.g., from human, livestock, or wildlife origins). Researchers believe that BST will be an important method for assisting in determining realistic TMDLs for fecal bacteria and implementation of BMPs for watershed restoration. Much of this research is being conducted in Virginia, spearheaded by Charles Hagedorn, Professor of Crop and Soil Environmental Sciences of the Virginia Institute of Technology. The method includes antibiotic resistance analysis (ARA), carbon source profiles, and pulsed field gel electrophoresis (PFGE) to determine sources of fecal pollution. PFGE is based on the method developed by George Simmons, Professor of Biology at the Virginia Institute of Technology. See Section 2.B for more on the use of BST for contamination source inventories.

Inorganic and Organic Chemicals

Approaches for detecting chemical and organic contaminants (including metals, and polar and nonpolar organics) include inductively coupled plasma mass spectrometry (ICPMS), polarography, liquid chromatography (LC), gas chromatography (GC), mass spectrometry (MS), graphite furnace atomic absorption spectrometry (GFAAS), "smell bells," and immunoassays. ILSI (1999) provides an overview of the advantages and disadvantages of these methods by type of contaminant, and further addresses whether they are high-, medium-, or low-cost approaches (ILSI, 1999; AWWA, 2002). In-depth descriptions of these systems have also been published by Drage et al. (1998) and Stoks (1998). AWWARF has performed research on arsenic and the relative importance of trace contaminants; a number of these sources appear in Appendix B.

Immunochemical measurements can be very effective for pesticides as well as for a range of other bioactive compounds such as pharmaceuticals or endocrine disruptors. Notably, where multiple samples can be analyzed simultaneously, the advantages of this technique (i.e., sensitive, rapid, and cost-effective) can be fully exploited (Meulenberg, 1997, 1998, in ILSI, 1999).

Early warning organics monitoring networks can detect chemical spills upstream of surface water intakes. Two examples of early warning monitoring are in place on the Ohio and Mississippi River systems. ORSANCO's Organics Detection System monitors the Ohio, Allegheny, Monongahela, and Kanawha Rivers; and the Early Warning Organic Compound Detection System (EWOCDS) monitors water quality along the lower Mississippi River. Both employ networks of gas chromatographs to detect potential carcinogenic and/or toxic substances, such as VOCs. In the event of a spill, these monitoring networks would provide early warning to water suppliers downstream, allowing them to close their intakes or take other measures to avoid contamination of the water system and resultant costly treatment or public heath impacts. The presence of these monitoring systems could also serve as a deterrent to illegal discharging of organic wastes or dangerous practices that could lead to accidental spills.

Radionuclides

Much of the contamination associated with radionuclides is associated with nuclear wastes at nuclear weapons plants and designated DOE and Department of Defense storage areas. For example, the Snake River aquifer is being monitored for migration of contaminant plumes associated with the Idaho National Environment and Engineering Laboratory (INEEL), and sites in Washington State are similarly monitored for contamination associated with nuclear wastes stored within the Hanford facility. Oak Ridge and Savannah River are additional DOE sites from which radioactive and transuranic wastes have migrated. A second source of radionuclide contamination is naturally-occurring radiation associated with radon (such as that associated with granite bedrock). Thus, much of the monitoring for radionuclides is done for ground water.

Radioactivity can be detected using nonspecific screening for beta and/or gamma radiation. Exceeding a preset threshold level may then lead to subsequent identification of specific nuclides by changing the energy window; notably in the case of gamma radiation, nuclides are characterized by their unique energy distributions (ILSI, 1999).

The USGS report, *Occurrence of Selected Radionuclides in Ground Water Used for Drinking Water in the United States: A Targeted Reconnaissance Survey,* focused intentionally on areas with known or suspected elevated concentrations of radium in ground water and collected 99 raw-water samples over a 6-month period from wells in 27 states, in 8 physiographic provinces. USGS analyzed ground water samples for radionuclide concentrations using alpha spectrometry (the primary method used), gamma spectrometry, beta counting, and combinations of these methods. No assessment of the effectiveness of these methods as detection tools is provided in the report, however.

Ongoing Research

One of the missions of the U.S. Army's Joint Service Agent Water Monitor Program (JSAWM) is to develop rapid, on-line capabilities to detect, identify, and quantify chemical and biological agents in potable water supplies. JSAWM is investigating several promising technologies including classic technologies (such as gas chromatography and mass spectrometry), evanescent wave (e.g., optical fibers, quartz crystal microbalance), and polymers (molecular imprinting, gels, nanoparticles, and biomimetics) for their utility as detection methods (Jensen, 1999, in ILSI, 1999).

On-going analytical methods research by AWWARF addresses *Microsporidia*, trace contaminants, and molecular models for virus identification. The need for additional real or near-real-time detection methodologies for biological agents deemed most likely to be used in bioterrorist activities is being addressed in ongoing WERF and AWWARF studies. Comparing the effectiveness of methods in detecting specific contaminants, including their speed of deployment, is the subject of several studies, slated for completion in 2003 and 2004.

WERF reports on a handheld advanced nucleic acid analyzer (HANAA), a real-time thermal cycler instrument capable of successfully amplifying DNA from *Cryptosporidium* and *E. coli*. Although it is an emerging technology, future commercial versions of the HANAA may be useful for laboratories performing PCR assays for waterborne pathogen detection.

USGS is currently conducting a national assessment of volatile organic chemicals in major aquifer systems and rivers (NAWQA). Thus far, the study has produced a national survey of methyl-t-butyl ether (MTBE) and other VOCs in community drinking water sources (June 2001), a gasoline oxygenate bibliography (updated in 2001), as well as several additional reports on

MTBE. USGS has also recently published a review of recent findings of contaminants and drinking water sources (Patterson and Focazio, 2001). Of particular interest are discussions on spatial and temporal distribution of contaminants; research to determine sources, transport, transformations, and fate of contaminants; and vulnerability assessments.

Additional research on BST methods is being done at the Virginia Institute of Technology at the Hagedorn Lab. Both molecular (genotype) and biochemical (phenotype) BST methods are under development. At present, BST can reliably determine if fecal bacteria are from human or animal sources, but it is less successful in differentiating between livestock and wildlife sources, and between individual livestock species; research is underway to improve its ability to discriminate among sources. The method is being used to develop several case studies of its effectiveness and to compare methods. Fecal sterols, including as coprostanol and epicoprostanol, are also showing promise as indicators of contamination by sanitary sewage; these molecular markers are better indicators of human wastes than fecal coliforms (Pitt et al., 2000).

EPA's Office of Science and Technology (OST) is conducting a field study across the U.S. to determine the necessity of monitoring for both bacterial and viral indicators (dual indicators). The study will evaluate the use of new laboratory aid documents to facilitate the use of EPA Methods 1601 and 1602 for coliphage analysis, as well as the applicability of the methods to various ground water samples. The study is expected to be completed in December 2002.

EPA, in developing the Ground Water Rule, reviewed 17 studies on the occurrence of pathogens and indicators, and summarized the findings in the Ground Water Rule Occurrence and Monitoring Document (EPA, 2002). These studies are described in Appendix B. In the Occurrence and Monitoring Document, EPA also describes several viral pathogen monitoring methods under development, including PCR, reverse transcription polymerase chain reaction (RT-PCR), and integrated cell culture PCR (ICC/PCR). EPA believes that these methods, while promising and useful in research, should be considered under development; they are currently too expensive and complex for field use.

Work at DOE's Sandia National Laboratories is focusing on developing chemical sensors, including one for monitoring of ground water for a wide variety of chemicals. Sandia is sponsoring research into the development of a microsensor monitoring system that can monitor and characterize VOCs in ground water to meet the need for accurate, inexpensive, real-time, in-situ analyses with remotely operated sensors (Ho et al., 2001). Sandia is also preparing to field test a lightweight, portable chemical vapor detection system that shows promise for rapid detection of chemicals in the environment. An array of seven surface acoustic wave (SAW) sensors with different chemically sensitive thin film coatings can identify 18 different VOCs in minutes.

AWWA and the Association of Metropolitan Water Agencies (AMWA) are working to address security issues for drinking water systems. AWWA is training water system staff on security issues. AMWA established the Critical Infrastructure Protection Advisory Group to coordinate efforts within the water sector to address protection of the nation's water infrastructure from physical and cyber-threats. Both organizations maintain a great deal of information related to terrorism and security on their web sites.

Research Needs

Continued research on additional **real or near-real-time pathogen and virus detection methodologies** is needed, especially for those viruses and the pathogens deemed most likely to be used in bioterrorist activities. As noted at the Water Security Summit, there is a need to develop continuous real-time and near real-time biological monitoring systems that can rapidly detect intrusions into water distribution systems, such as through service connections and hydrants. Additional research on costs and reliability of real-time analytical methods in specific situations is also needed.

Promising detection technologies for chemical and radiological contaminants include remote sensing, combined (bio)sensors and analytical techniques such as capillary electrophoresis-immunoassays, fiber optics with molecular imprinting, and genetically engineered microorganisms. Continued research to fully develop these methods as reliable for rapid detection, especially for drinking water systems, is needed.

Understanding the **time of travel to surface water intakes** is also crucial to emergency response planning. Using fluorescent tracers is one possible avenue for research to better understand response times. Time of travel studies should include contamination sources upstream of drinking water intakes, such as RCRA and Superfund sites, waste water outfalls, and CSOs.

Research needs for **chemical early warning monitoring** include testing and application of promising technologies, interpretation of biological signals, and related institutional concerns (ILSI, 1999). Low-cost screening methods for emerging contaminants of concern, such as pharmaceuticals, algal toxins, metabolites of pesticides, and viruses, should be researched as well.

4.B. Response Systems

Research Question

What are the most efficient and effective methods for containing accidental or deliberate emergency situations in ground water and surface water supplies?

> ***Research Needs...***
>
> ✔ Containment methods to address existing and emerging contamination threats.
> ✔ Readiness to respond to the most-probable threats within a water supply area.

This section describes measures that may be taken to prevent or delay the spread of contaminants in surface and ground water used as drinking water supplies. Physical barriers such as booms and berms are discussed, especially with reference to surface water contaminations such as oil spills. Although there are many treatment technologies available to address contamination, they are not discussed here, as they are beyond the scope of this review, since source water protection is focused on preventing the contamination of water supplies.

State of the Science

A variety of technologies to prevent contaminants from entering ground water and surface water are available. Recent research is described below.

Ground Water

In the event of ground water contamination, effective response systems would delay the spread of contaminant plumes within the aquifer, either to deflect the contamination away from drinking water supply wells or to contain the plume until remediation efforts begin. The use of barrier technologies allows containment of expanding contaminant plumes and can reduce remediation costs (Mohanty, 2000). Containment methods are selected based on the anticipated remediation technology or based on the nature of the contaminants.

In the scientific literature, containment and remediation are often evaluated together, as containment is often considered as an option for responding to contamination. For example, of six ground water remediation options identified by Gorelek et al. (1993), three focused on containment—including stabilization or diversion of contaminant materials and monitoring of contaminant levels until the plume dissipates (e.g., through natural attenuation) or worsens. Both Merriman (1999) and Guelph have described containment mechanisms that are part of restoration or remediation strategies (Gorelek et al., 1993, in ILSI, 1999).

The principle mechanism for containing dense nonaqueous-phase liquids (DNAPLs) is a physical impermeable barrier. The chlorinated organic compounds that comprise the DNAPLs at many waste sites have low solubilities in water. As a result, when released in the subsurface, they typically do not completely dissolve in the ground water, but remain largely as a separate, nonaqueous-phase liquid, and create a persistent source of ground water contamination as they slowly dissolve into the water column.

Additional methods used for underground contaminant containment are slurry trenching, used to provide a barrier, and the introduction of polymeric and silica gel materials to provide barriers against NAPLS and aqueous organic and ionic contaminants.

Surface Water

Where surface water supplies are contaminated, technologies such as berms and booms may be used to prevent or delay expansion of contaminated areas. Berms are constructed of naturally occurring material to form a small hill that can prevent erosion or reduce runoff. Berms are generally used in areas where organic, chemical or radiological contamination has occurred. While many berms are composed of soil and/or rip-rap and other manufactured materials, some may be constructed from rock or uncontaminated mine tailings.

Most of the literature on surface water pollution containment technologies focuses on oil spills, which provide some of the largest and most environmentally devastating forms of pollution, affecting essentially all water body types and adjacent lands. Booms, oil skimmers, absorbent pads and mats, storage trailers and tanks, and chemical solvents and foams are used to address oil spills.

EPA’s Oil Pollution Prevention Regulation (40 CFR Part 112) addresses the oil spill prevention provisions contained in the Clean Water Act of 1972 (as amended). The regulation forms the basis of the SPCC program which seeks to prevent oil spills from some above-ground and all underground storage tanks. SPCC plans are designed to ensure that facilities put in place containment and other countermeasures that would prevent oil spills that could reach navigable waters. SPCC plans must include operating procedures that prevent oil spills; control measures to prevent a spill from reaching navigable waters; and countermeasures to contain, clean up, and mitigate the effects of an oil spill that reaches navigable waters. Each facility must describe the containment and/or diversionary structures or equipment it has available to prevent discharged oil from reaching navigable waters. See also the discussions of BMPs for above-ground and underground storage tanks in Sections 3.C and 3.D.

A considerable amount of information is available concerning oil spill technologies. At least 10 companies maintain websites on oil spill technologies and products. These include oil skimmers, containment booms, response vessels, incinerators, polypropylene absorbents for oil and chemical spills, absorbent pads, mats, booms and spill response kits, and inflatable oil spill booms. No sources were found that evaluated either the effectiveness or the efficiency of these products.

Marine pipe pilings and sheet pilings, developed for the U.S. Army Corps of Engineers, use a new type of patented interlocking system called Uniloc. Developed by DuPont Chemicals, the Uniloc system provides an in-the-ground barrier against the migration of chemical spills and toxic materials. For toxicity containment systems, Uniloc products can be used for toxic waste retention, underground hydrocarbon tank leak containment, farmland pesticide and fertilizer run-off control, segregation, and disposal of hydrocarbons from highway runoff.

Response Systems

Since 1989, the Upper Mississippi River Basin Association (UMRBA) has provided staff support for the Upper Mississippi River (UMR) Hazardous Spills Coordination Group, which includes representatives of the state and federal agencies that play a role in spills contingency planning and response on the river. Among the group's accomplishments are development and maintenance of the Upper Mississippi River Spill Response Plan and Resource Manual, adopted by the five state and four federal agency members of the Spills Group through a memorandum of agreement. The UMR Spill Response Plan is designed to complement broader regional and national contingency plans by addressing issues and concerns related specifically to spill response on the Upper Mississippi River. The resource manual portion of the document includes important information about potential spill sources, vulnerable resources, and responses.

Pursuant to the Oil Pollution Act of 1990, the UMRBA is also engaged in a related cooperative planning and mapping effort. Funded largely by EPA Region 5, project partners also include USGS's Upper Midwest Environmental Sciences Center and the Great Lakes Commission. The mapping initiative is known as the Inland Sensitivity Mapping Project. Using GIS applications, the partners are producing integrated maps showing potential spill sources, sensitive human and environmental resources, and other important features. In addition, this cooperative effort is developing local, sub-area contingency plans for areas including Minneapolis-St. Paul, the Quad Cities of Illinois and Iowa, and greater St. Louis.

The National Research Council (NRC) publication *Facing the Unexpected: Disaster Preparedness and Response in the United States* (2001) presents findings from disasters around the world over the past 25 years. The authors explore how these findings can improve disaster programs and help identify remaining research needs. The authors review the influences that shape the U.S. governmental system for disaster planning and response, the effectiveness of local emergency agencies, and the level of professionalism in the field. They also compare technological versus natural disasters and examine the impact of technology on disaster programs (Tierney et al., 2001).

Ongoing Research

Some of the technologies for containing metals and radionuclides are in the development stage and include subsurface barriers, in situ vitrification, solidification and stabilization, permeable reactive barriers, in situ redox manipulation, and natural attenuation. Because metal and radionuclide contaminants are generally non-degradable, treatment technologies must involve some form of mobilization of the contaminant (in order to move it to a location where it can be treated) or immobilization (in order to stabilize it in place and prevent further spreading), and sometimes a combination of both.

Research Needs

Given recent concerns about newly emerging contamination threats (e.g., bioterrorism agents) that could potentially affect the health of large numbers of people and for which treatment may be expensive or unavailable, water system operators and planners need to be able to react quickly to contain these substances when and if they are detected. The **applicability of the containment methods described above to biological agents and pathogens** may warrant further research.

Planners should be prepared to **respond to the threats** they are most likely to face. Contamination response research initiatives should parallel those for the source inventory process (see Section 2.B) that will help decision-makers be aware of possible contaminants, monitor for them, and quickly contain spills or releases.

Appendix A: Office of Water Proposed Social Science Research Needs: Source Water Research

Number	Project Name	Description
Source Water Protection Projects		
1.	Cost/Benefits of Source Water Protection	Investigate cost/benefit tradeoffs to source water protection as compared to treatment and contamination clean up/restoration for ground water and surface water-based public water supplies (either literature analysis, or comparisons across real communities over time– different communities implementing different types of regulatory or non-regulatory prevention measures).
2.	Cost/Effectiveness of Source Water Protection	Investigate cost/effectiveness tradeoffs in different communities given different measurable goals (such as water quality goals), possibly using different regulatory and non-regulatory techniques, over time.
3.	Benefits of Source Water Protection Relative to Unregulated Contaminants	Develop methodologies for estimating treatment cost avoidance where source water protection can avoid new treatment costs being incurred for unregulated contaminants (e.g., pharmaceuticals, unregulated endocrine disruptors, unregulated bacteria and viruses)
4.	Effectiveness of Public Awareness Campaigns for Source Water Assessments	Conduct Before/After Studies to measure public awareness of source water assessment information given various outreach campaigns in different communities.
5.	Effectiveness of Source Water Assessments in Generating Prevention Actions in Different Watersheds and Wellhead Areas.	Conduct Before/After Studies to measure nature of regulatory and non-regulatory prevention actions implemented in communities with similar outreach campaigns to make source water assessments available to the public.

Appendix B: Bibliography of Research

This Appendix includes a sampling of the recent research available on the topics discussed in this paper. It is not intended to be an exhaustive presentation of the body of scientific literature.

Cross-Cutting Research

The following research efforts relate to more than one of the research topic areas in this research paper. Some of the studies here are also presented in the specific topic areas that follow, e.g., where they are referenced in the body of the research paper.

Bice, L.A., R.D. Van Remortel, N.J. Mata, and R.H. Ahmed. (2000) Source Water Assessment Using Geographic Information Systems. Prepared for U.S. EPA, Office of Research and Development. EPA/600/R-00/067. May. Retrieved January 23, 2002 from the World Wide Web: http://www.epa.gov/ORD/NRMRL/wswrd/gis.html

> This document provides guidance to states, municipalities, and public water utilities for assessing source waters using geographic information system (GIS) technology. The GIS platforms can be used to organize, analyze, and manipulate available data and generate new data for source water protection areas, as well as provide capabilities for presenting the data to the public in various forms, including maps and tables. Included as appendices to this document are three case studies demonstrating the use of selected GIS-based software and hydrologic models to conduct hypothetical source water evaluations.

Bouraoui, F. and T.A. Dillaha. (2000) ANSWERS-2000: Non-Point-Source Nutrient Planning Model. Journal of Environmental Engineering 126(11):1045-1055.

> ANSWERS-2000, a non-point-source planning model was modified to simulate long-term nitrogen (N) and phosphorus (P) transport from rural watersheds. The model simulates infiltration, evapotranspiration, percolation, and runoff and losses of nitrate, adsorbed and dissolved ammonium, adsorbed total Kjeldahl N, and adsorbed and dissolved P losses. Eight soil nutrient pools are modeled: stable organic N, active organic N, nitrate, ammonium, and stable mineral P, active mineral P, organic P, and exchangeable P. The model was validated on two small watersheds without calibration and on a large watershed with calibration of only the sediment detachment parameters. Predicted cumulative runoff, sediment, nitrate, dissolved ammonium, adsorbed total Kjeldahl N, and orthophosphorus P losses were within a factor of 2 of observed values (-40 to +44% of observed values). Predictions of individual runoff event losses were not as accurate (-98 to +250%). The model seriously underpredicted adsorbed ammonium losses by up to 97%, and additional work is recommended on this submodel. In a practical application, the use of the model in evaluating the cost-effectiveness of alternative management scenarios was demonstrated.

Camp Dresser and McKee, Inc. Electronic Watershed Management Reference Manual—Version 2.0. AWWARF Project No. 2651. To be completed in 2002.

> This project will update and expand Version 1.0 (project #903) to include changes in the SDWA amendments, new advances in watershed management, and Canadian and UK initiatives.

Clausen, J.C. and D.W. Meals, Jr. (1989) Water Quality Achievable with Agricultural Best Management Practices. Journal of Soil and Water Conservation 44(6):593-596. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> Water quality in runoff from agricultural areas under best management was compared with water quality standards, where appropriate, and with other measures of treated water, thereby defining the water quality achievable by using best management practices. The study draws upon results obtained from 7 years of water quality monitoring in the LaPlatte River and St. Albans Bay watersheds in Vermont of BMPs implemented for manure management, barnyard runoff, and milkhouse wastes. These studies include long-term stream monitoring for sediment and nutrient concentration and load, as well as intensive evaluation of the treatment effectiveness of certain BMPs, such as vegetated filter strips and manure storage, on concentration and export of sediment, nutrients, and bacteria. Results indicate that BMPs may be highly effective in reducing pollutant concentrations and loads, but runoff may continue to exceed water quality criteria.

Conservation Technology Information Center. Source Water Protection Alliances Between Water Utilities and Agricultural Operations. AWWARF Project No. 2781. To be completed 2003.

> This project will convene a workshop of representatives from the drinking water and agricultural communities, and utilize case studies and existing partnership-building approaches to identify strategies for building successful alliances with agricultural producers in the watershed. Will also demonstrate the use of these strategies by establishing an alliance, implementing specific source water protection measures, and evaluating the impact of the source water protection measures on source water quality.

Donigian, A.S., R.V. Chinnaswamy, A.S. Patwardhan, and R.M. Jacobson. (1996) Watershed Modeling of Pollutant Contributions and Water Quality in the LeSueur Basin of Southern Minnesota. *In*: Proceedings Watershed '96. June 8-12, 1996, Baltimore, Maryland. Retrieved October 26, 2001 from the World Wide Web: http://www.epa.gov/owow/watershed/Proceed/donigian.html

> As part of the Minnesota River Project, the LeSueur Watershed is being modeled with the U.S. EPA Hydrologic Simulation Program - FORTRAN (HSPF) to identify and quantify

the relative pollutant contributions from both point and nonpoint sources, and to help evaluate the effects of alternative agricultural BMPs on water quality and pollutant loadings to the main stem of the Minnesota River. This paper briefly describes the model application procedures, watershed representation and preliminary calibration results, along with indications of future modeling directions.

Environmental Finance Center Network. Unified Source Water Protection Projects. Available on the World Wide Web at: http://efc.unm.edu/Source%20Water%20Project%20Status/SWprojectstatus.htm.

EFC is working to develop resource-based or unified source water protection plans for clusters of communities in seven states (North Carolina, Oregon, Colorado, Texas, New Mexico, Idaho, West Virginia). The pilot projects are bringing together drinking water systems that share a common drinking water supply source together with other land use authorities and to have these jurisdictions work collaboratively to develop and implement unified source water protection measures. This approach has the potential for greater collaboration in source water protection efforts and may permit communities to achieve greater control measures in protecting their drinking water from contamination.

Hammen, J.L. and P.J. Gerla. (1994) A Geographic Information Systems Approach to Wellhead Protection. Water Resources Bulletin 30(5):833-840.

These elements encompass technical, administrative and educational considerations. In functioning both as a research tool and as a decision support system, a geographic information system (GIS) is shown to have proven utility in addressing these issues. This article describes the application of common GIS functionality in facilitating a comprehensive wellhead protection scheme for an agricultural municipality in North Dakota.

McCarthy, M. and R. Dodd. (1995) Cost-Effectiveness and Targeting of Agricultural BMPs for the Tar-Pamlico Nutrient Trading Program. Paper presented at Watershed ‘96 Proceedings. http://www.epa.gov/owowwtr1/watershed/Proceed/mccarthy.html

The Tar-Pamlico Nutrient Trading Program is a pioneering effort to more effectively manage nutrient inputs to an estuary. This paper discusses some of the technical work that supports Program implementation. In order to help the Program participants set a reasonable cost for trading nitrogen or phosphorus between point and nonpoint sources and understand how cost effective different BMPs are, we developed cost-effectiveness estimates (expressed as $/kilogram of nutrient load reduced) for cost-shared agricultural BMPs in the Basin.

New England Interstate Water Pollution Control Commission. (2000) SWAP Technical Assistance Document: The Application of GIS Technology and Data Management in States' Source Water Assessment Programs. October. Retrieved January 8, 2002 from the World Wide Web: http://www.neiwpcc.org/swap.pdf

This report addresses states' SWAP/ source protection related data quality, coordination, management, and distribution issues and concerns. This document highlights five states' approaches (Pennsylvania, Washington, Ohio, Iowa, and Nevada) to using GIS in their Source Water Assessment Programs.

Sharpley, A.N., B. Foy, and P. Withers. (2000) Practical and Innovative Measures For the Control of Agricultural Phosphorus Losses to Water: An Overview. Journal of Environmental Quality 29(1):1-9. Retrieved January 8, 2002 from the World Wide Web: http://home.wlu.edu/~blackmerh/bio182/pfiesteria.html

This paper provides a brief overview of P management strategies to maintain agricultural production and protect water quality that were discussed at the conference, "Practical and Innovative Measures for the Control of Agricultural Phosphorus Losses to Water," sponsored by the Organization for Economic Cooperation and Development and held in Antrim, Northern Ireland, June 1998.

Stroud Water Research Center, et al. Evaluation of Sources of Pathogens and NOM in Watersheds. AWWARF Project No. 251. To be completed in 2001.

This project will determine the distribution and densities of Giardia and Cryptosporidium and the concentrations of NOM (natural organic matter) in watersheds, and evaluate potential sources in field studies. It will develop potential source control strategies that will mitigate the concentrations of these contaminants in influent water resulting in potential treatment savings.

Connecticut Department of Public Health and Connecticut Department of Environmental Protection (CDPH and CDEP). (1999) State of Connecticut Source Water Assessment Program: Work Plan. Retrieved January 22, 2002 from the World Wide Web: http://www.dph.state.ct.us/BRS/WSS/swap.htm

Duncan, D., D.T. Pederson, T.R. Shepherd, and J.D. Carr. (1991) Atrazine Used as a Tracer of Induced Recharge. Ground Water Monitoring Review 11(4):144-150.

Ford, T.E. (1999) Microbiological Safety of Drinking Water: United States and Global Perspectives. Environmental Health Perspectives 107(1):191-206.

Miller, T.L. and W.G. Wilber. (1999) Emerging Drinking Water Contaminants: Overview and Role of the National Water Quality Assessment Program (Ch 2.). *In*: Identifying Future Drinking Water Contaminants. National Academy Press, Washington, DC.

Oregon Department of Environmental Quality (ODEQ) and Oregon Health Division (OHD). (2000) Source Water Assessment Plan. Retrieved January 18, 2002 from the World Wide Web: http://waterquality.deq.state.or.us/wq/dwp/SWAPCover.htm

Pennsylvania Department of Environmental Protection (PADEP). (2000) Pennsylvania Source Water Assessment and Protection Program. Retrieved January 15, 2002 from the World Wide Web: http://www.dep.state.pa.us/dep/deputate/watermgt/wc/subjects/srceprot/default.htm

Schilling, K.E. and R.D. Libra. (2000) The Relationship of Nitrate Concentrations in Streams to Row Crop Land Use in Iowa. Journal of Environmental Quality 29(6):1846-1851.

University of North Carolina. The Broad/2d Broad Source Water Project: Protecting and restoring the outstanding quality of the Broad River headwaters. Retrieved May 9, 2002 from the World Wide Web at: http://www.efc.unc.edu/projects/SourceWater/BroadSWPHome.htm

> The efc@unc has begun work on a source water protection plan with a group of communities in the upper Piedmont and Blue Ridge Mountains in North Carolina. This planning effort is one of the first pilot projects growing out of the efforts by U.S. EPA and the states to assess potential contaminants for public water supplies across the country. The pilots seek to understand how to help different local governments work together to protect their shared drinking water resources.

U.S. EPA. (1990) Hazard Ranking System; Final Rule. December 14. Federal Register 55(241):51531-51667 [55 FR 51531].

U.S. EPA. (1998) Biological Indicators of Ground Water – Surface Water Interaction: Update. EPA Report 816/R-98-018, Office of Water, U.S. EPA, 39 pp.

U.S. EPA. (1999a) Guidance Manual for Conducting Sanitary Surveys of Public Water Systems; Surface Water and Ground Water Under the Direct Influence (GWUDI). EPA Report 815/R-99-016, Office of Water, U.S. EPA, 182 pp.

USGS. (2001a) Virginia Aquifer Susceptibility Study: Dating of Ground Water for Source Water Assessment Screening. Retrieved January 17, 2002 from the World Wide Web: http://va.water.usgs.gov/projects/va123.html

Virginia Department of Health (VDOH). (1999) Virginia Source Water Assessment Program. Retrieved January 22, 2002 from the World Wide Web: http://www.vdh.state.va.us/dwse/swap.htm

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. (1999) Ground Water and Surface Water: A Single Resource. U.S. Geological Survey Circular 1139. U.S. Government Printing Office, Denver, Colorado, 79 pp.

Wisconsin Department of Natural Resources (WIDNR). (1999) Wisconsin's Source Water Assessment Program Plan. Retrieved January 8, 2002 from the World Wide Web: http://www.dnr.state.wi.us/org/water/dwg/gw/SWP.HTM

Standard Setting

Ongoing Research

EPA, Office of Science and Technology. (2002) Draft Strategy for Water Quality Standards and Criteria: Strengthening the Foundation of Programs to Protect and Restore the Nation's Waters. EPA-823-R-02-001. May.

> This Strategy identifies strategic actions for OST to take to strengthen and improve the WQS program. It reflects a review of the existing WQS program in the context of other programs, including source water protection. The strategy identified 28 strategic actions to accomplish over the next 7 years.

EPA, Office of Research and Development. (2002) Drinking Water Research Program Multi-Year Plan. March.

> ORD initiated a new research planning process that is based on the use of Multi-Year Plans (MYPs) developed for each major research program. The Drinking Water MYP describes ORD's FY02-08 research program to support the regulatory activities of the EPA Office of Water. The drinking water research program is described in the context of a long-term goal, annual performance goals, and annual performance measures.

Source Water Assessment Process

Delineation of Source Water Areas

Ground Water Delineation

Recent Research

Allen-Lafayette, Z., W. Mennel, and S. Spayd. (1998) Dover Township Study Area, New Jersey, Well Head Protection Areas. Soller, D.R. (editor) U. S. Geological Survey, Reston, VA, United States, Digital mapping techniques '98; workshop proceedings, OF 98-0487, p. 104, 1998. Meeting: Digital mapping techniques '98, Champaign, IL, United States, May 27-30, 1998.

This map was prepared to assist the New Jersey Departments of Environmental Protection and Health and Senior Services in their evaluation of a possible childhood cancer cluster in parts of Dover Township, Ocean County. Ground water from domestic and public supply wells is the sole source of water for drinking and other domestic uses in the study area. Public community supply wells are shown along with their respective Well Head Protection Areas developed from ground-water modeling. Special coverages were developed from ground-water models to show the potential flow pathlines from the Reich Farm pollution plume if the well field was not pumping.

Anderman, E.R. and M.C. Hill. (1998) Improving Ground-water Flow Model Calibration with the Advective-Transport Observation (ADV) Package to MODFLOWP. U.S. Geological Survey Fact Sheet FS-059-98. Retrieved October 21, 2001 from the World Wide Web: ftp://water.usgs.gov/public/software/ground_water/Modflowp/doc/fs05998.pdf

Anderman, E.R. and M.C. Hill. (1999) A New Multi-stage Ground-water Transport Inverse Method, Presentation, Evaluation, and Implications. Water Resources Research 35(4):1053-1063. Retrieved October 31, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.99.html#anderman.hill

This study evaluates a new mathematical method that links decoupled flow and transport models. The method is evaluated in a test case.

Anderman, E.R. and M.C. Hill. (2000) MODFLOW-2000 The U.S. Geological Survey Modular Ground-Water Model – Documentation of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 00-342, 89 pp.

This fact sheet describes the benefits of the Advective-Transport Observation (ADV) Package addition to MODFLOWP.

Anderson K.S., A.A. Ripley, and R.I. Thun. (1992) Analysis of Multivariate Plots as One Tool in the Delineation of Hydrocarbon Plumes. Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration; November 4-6, 1992, Houston, Texas (Ground Water Management Book 14): .573-582.

Analysis of multivariate plots was used as one investigative tool to define the distribution of hydrocarbons beneath two adjacent service station facilities. Multivariate plots show relative ratios of BTEX compounds plotted on two axes, X and Y. Once generated, the plots were located on site maps to facilitate evaluation of relative BTEX ratio distributions. Multivariate plots were used in conjunction with liquid-phase hydrocarbon characterization, water level measurements, BTEX concentration trend analyses, and subsurface characteristics to define two separate and distinct hydrocarbon plumes across two adjacent facilities. The digital model grapher was used to graph the multivariate plots.

Aravena, R. M.L. Evans, J.A. Cherry. (1993) Stable Isotopes of Oxygen and Nitrogen in Source Identification of Nitrate from Septic Systems. Ground Water 31(2):180-186

Stable isotopes, nitrogen-15 and oxygen-18, have been used as tracers to differentiate a contaminant nitrate plume emanating from a single domestic septic system, in a ground water system characterized by high and similar nitrate content outside and inside of the contaminant plume. A good delineation of the nitrate plume of septic origin was obtained using nitrogen-15 analysis in nitrate. The nitrogen-15 content of the nonplume nitrate is in agreement with the sources of nitrate: solid cattle manure, synthetic fertilizer (ammonium-nitrate), and soil organic nitrogen, at the study site. Oxygen-18 data indicated that nitrification of ammonium is the main process responsible for formation of nitrate at the study site. Oxygen-18 in ground water clearly delineated the ground water plume associated with the septic system and suggests that this tracer should be considered in studies related with contaminant plumes of different origin. Delta values (compositional proportions) of nitrogen-15 typical of commercial fertilizers, soil organic nitrogen nitrate, and human and animal waste nitrate are mentioned along with delta values of oxygen-18 in atmospheric oxygen, synthetic fertilizers, water at the site, and ground water nitrate.

Bair, E.S., and T.D. Lahm. (1996) Variations in Capture-Zone Geometry of a Partially Penetrating Pumping Wells in an Unconfined Aquifer Ground Water. 34(5): 842-852.

The influence of hydrogeology and well design upon the depth and width of capture zones was examined by mathematically simulating partially penetrating wells of various depths withing a uniform and steady ground water flow regime where regional hydraulic gradient and anisotropy were varied. Graphs obtained from MODFLOW simulations show how to incorporate depth of recovery wells penetration, regional hydraulic gradient, and anisotropy into capture zone design. An equation is provided for estimating the distance from a partially penetrating well where ground water flow is predominantly horizontal. Sources of anisotropy in aquifers are discussed. Values of horizontal hydraulic conductivity and rations between horizontal and vertical hydraulic conductivity are tabulated for glaciofluvial and fluvial/deltaic sediments from various locations.

Baker, C.P., M.D. Bradley, and S.M. Kaczor Bobiak. (1993) Wellhead Protection Area Delineation: Linking Flow Model with GIS. Journal of Water Resources Planning and Management 119(2):275-287.

The Rhode Island Department of Environmental Management (RIDEM) is using the Uniform Flow analytical model, in conjunction with hydrogeologic mapping, for WHPA delineation around large public supply wells completed in stratified drift in Rhode Island. A geographic information system (GIS) calculates variables for input into the model, transforms model output into geographically referenced data layers, and provides mylar

overlays for final hydrogeologic mapping of the WHPA. RIDEM hydrogeologists provide study area boundaries, run the model on a personal computer based program, and delineate the final WHPA on mylar overlays. Maps of the WHPAs and other hydrogeologic data will be provided to communities and water suppliers and will be the basis for local wellhead protection planning required under the Rhode Island Wellhead Protection Program.

Bakker, M. (2001) An Analytic, Approximate Method for Modeling Steady, Three-dimensional Flow to Partially Penetrating Wells. Water Resources Research 37(5): 1301-1308.

An analytic, approximate solution is derived for the modeling of three-dimensional flow to partially penetrating wells. The solution is written in terms of a correction on the solution for a fully penetrating well and is obtained by dividing the aquifer up, locally, in a number of aquifer layers. The resulting system of differential equations is solved by application of the theory for multiaquifer flow. A number of comparisons are made to existing three-dimensional, analytic solutions, including radial confined and unconfined flow and a well in a uniform flow field.

Bakker, M., and O.D.L. Strack. (1996) Capture Zone Delineation in Two-Dimensional Groundwater Flow Models. Water Resource Research 32(9): 2215-2224.

Barlow, P.M., L.A. DeSimone, and A.F. Moench. (2000) Aquifer Response to Stream-stage and Recharge Variations, II. Convolution Method and Applications. Journal of Hydrology 230:211-229. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.00.html#moench2

Functions developed in the companion paper to Moench and Barlow (see below) for several cases of hydraulic interaction between a stream and a confined, leaky, or unconfined aquifer, are used to calculated the hydraulic properties of a system in response to stream-stage fluctuations and basinwide recharge or loss. Two computer programs developed from these functions were then applied to the analysis of the hydraulic interaction between two stream-aquifer systems in the northeastern and central U.S. The results of these analyses are compared with the results of previously conducted, more complicated, tests.

Barlow, P.M. and A.F. Moench. (1999) WTAQ - A Computer Program for Calculating Drawdowns and Estimating Hydraulic Properties for Confined and Water-table Aquifers. U.S. Geological Survey Water- Resources Investigations Report 99-4225. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.99.html#barlow.moench

The computer program *WTAQ* calculates hydraulic-head drawdowns in a confined or water-table aquifer that result from pumping at a well. Three sample problems illustrate use of *WTAQ* for estimating hydraulic properties.

Bartel, L.C. (1989) Delineation of Brine Drilling-fluid Loss in an Unsaturated Zone - Application to Contamination Monitoring. Proceedings of the Third National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods (May 22-25, 1989, Orlando, Florida): 841-854

Pre- and post-drilling Controlled-Source Audio Frequency Magnetotelluric (CSAMT) surface electromagnetic geophysical surveys were used to map and monitor the loss of the brine drilling fluid during the drilling of a hydrology test well at the h-11 hydropad near the Waste Isolation Pilot Plant (WIPP) near Carlsbad. The purpose of these surveys was to: 1) determine the base line resistivity structure prior to drilling, 2) delineate the extent of resistivity changes caused by the loss of the brine drilling fluid, and 3) provide information on the fracture system within the Culebra aquifer at the h-11 hydropad. The following are addressed: the definition of apparent resistivity, the CSAMT technique, and CSAMT geophysical survey results and data analysis. Results of model calculations (using the digital model EM3DS) are shown.

Becker, M.W. and A.M. Shapiro. (2000) Tracer Transport in Fractured Crystalline Rock: Evidence of Nondiffusive Breakthrough Tailing. Water Resources Research 36(7):1677-1686. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.00.html

Study presents a field example where tracer tests were conducted in a fractured crystalline rock. Finding has implications for the interpretation of tracer tests designed to measure matrix diffusion and the prediction of contaminant transport in fractured rock.

Bossong, K. (2002) An Investigation of Ground-Water Resources in the Foothills of the Rocky Mountains near Denver, Colorado. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 23.

The principle data collected and assimilated in the investigation were field evaluations of fracture networks at the outcrop scale, records of well construction details, water-quality analyses of samples collected from stream and well networks, physical measurements of precipitation, evapotranspiration, and runoff from the watershed. The water-quality data are the basis for findings that indicate ground-water quality has been influenced by activities associated with the residential nature of the watershed. In addition, findings from synthesis of the data and modeling, have led to estimates indicating that recharge to the fractured rock aquifer varies according to geology and, overall, is comparable to contemporary estimates for the amount of water withdrawn for domestic use.

Bradbury, K.K., Evans, J., Yonkee, A, and T. Lachmar. (2002) Structural Characteristics of Folded and Fractured Sedimentary Bedrock Aquifers Near Park City, Utah. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 38.

> Study characterizes structures potentially influencing ground water flow in the Pinebrook subdivision, a housing development within the Snyderville basin experiencing abrupt hydrogeologic changes in their water supply wells. The goal of this study was to provide a field-based analysis and a conceptual model that could potentially be used for ground water management and planning decisions.

Bradbury, K.R., and T.W. Rayne. (2002) The Sturgeon Bay Wellhead-Protection Project: Delineation of Contributing Areas for Municipal Wells in Fractured Dolomite. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 10-13.

Brand, C. (2002) Colorado's Source Water Assessment and Protection (SWAP) Program: Delineation of Source Water Assessment Areas (SWAAs). In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 45.

Chao Shan. (1999) An Analytical Solution for the Capture Zone of Two Arbitrarily Located Wells. Journal of Hydrology 222(1-4): 123-128.

> A capture zone of pumping well(s) is an aquifer with regional groundwater flow has been widely used to help design a pump-and-treat system for groundwater containment and remediation. Based on the theorem of potential and the principle of superposition, an analytical solution is derived in this study to calculate the capture zone for two arbitrarily located wells that pump water from a confined aquifer at an equal flow rate. The general two-well capture zone is composed of two sub-capture zones, one for each well. The shapes of the two sub-capture zones and their relative locations change with variations of the orientation and the separation of the two wells. The solution can be useful in verifying available numerical codes, as well as in solving practical field problems.

Christensen, S. and Cooley, R.L. (1999) Evaluation of Prediction Intervals for Expressing Uncertainties in Groundwater Flow Model Predictions. Water Resources Research 35(9):2627-2039. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.99.html

> This study tested the accuracy of 95% individual prediction intervals for hydraulic heads, streamflow gains, and effective transmissivities computed by groundwater models of two Danish aquifers. Conclusion is that for the groundwater models of the two real aquifers the individual prediction intervals appear to be accurate.

Cleary, T.C.B.F. and R.W. Cleary. (1992) Delineation of Wellhead Protection Areas: Theory and Practice. Pollution, Protection and Control of Groundwater Proceedings of the IAWPRC

International Seminar, held in Porto Alegre, Brazil, 20-21 September 1990. 1st ed. Oxford [England] ; New York : Pergamon Press: 239-250.

Cole B.E., and S.E. Silliman. (2000) Utility of Simple Models for Capture Zone Delineation in Heterogeneous Unconfined Aquifers. Ground Water 38(5): 665-672.

> Monte Carlo simulation was used to examine the utility of simple (homogeneous / isotropic) models for the delineation of wellhead protection areas in heterogeneous, statistically anisotropic, unconfined aquifers. Capture zone geometry was investigated under two hydrologic conditions: regional gradient negligible compared to pumping and significant regional gradient compared to the local gradient due to pumping. Variability of capture zone geometry is quantified in terms of simple measurements and the probability of inclusion in the capture zone of a series of hypothetical contaminant source locations. These results indicate that substantial uncertainty exists in the delineation of a wellhead capture zone.

Cole, B.E., and S.E. Silliman. (1997) Capture Zones for Passive Wells in Heterogeneous Unconfined Aquifers. Ground Water 35(1): 92-98.

> For wells having limited impact on regional aquifer hydraulics, the variability of the capture zone is defined both in terms of travel distance and distance perpendicular to the flow path traced under homogeneous, isotropic conditions. Variability was defined through Monte Carlo simulation of possible spatial distributions of the hydraulic conductivity given little information for a field site. A system of safety factors is suggested for homogeneous, isotropic analysis to accommodate lack of knowledge regarding the hydraulic conductivity at a given site.

Colorado Department of Public Health and Environment. (2000) Delineation of Source Water Assessment Areas. *In*: Chapter 3: Colorado Source Water Assessment and Protection (SWAP) Program Plan. Water Quality Control Division. Available on the World Wide Web at: http://www.cdphe.state.col.us/wq/sw/swapdrft.html

> This chapter describes how Colorado will delineate source water assessment areas. Addresses delineation approaches, methods, and areas with ground water / surface water interactions.

Cooper, B.C., J.R. Frankenberger, and F. Whitford. (2000) Wellhead Protection for Safe Drinking Water in Indiana: Management Options for Wellhead Protection. Purdue Extension. WQ-37. 8 p. Retrieved May 6, 2002 from the World Wide Web: http://www.ecn.purdue.edu/SafeWater/wellhead/Management.pdf

> This publication provides an overview of wellhead protection management options. It can be used by wellhead protection planning teams, water supply operators, and public

officials, such as the Plan Commission, to develop a framework for wellhead protection management.

Davis, R.K., and P.E. White. (1999) Substantiating the Need to Base Delineation of Source Water Assessment and Protection Areas on Hydrogeology in Mantled Karst Aquifers. Ground Water Supply Issues in the Next Century, 1999 Abstract Book, NGWA National Convention and Exposition, December 3-6, 1999, Nashville: 29-30.

A management tool is being developed for public water utilities to enhance the protection of their drinking water. Source water protection areas have been identified and the potential contaminant sources assessed. In the shallow karstic aquifer region, a fixed radius of ½ mile surrounding the intake has been designated as the protection area.

Day-Lewis, G.D., J.W. Lane, Jr., P.A. Hsieh, and S.M. Gorelick. (2001) Characterizing Fractured Rock Aquifers Using RADAR, Tracer and Hydraulic Data. *In*: Fractured Rock 2001 Conference, Proceedings, Toronto, Ontario, March 26-28, 2001. Retrieved November 5, 2001 from the World Wide Web:
http://water.usgs.gov/ogw/bgas/publications/FracRock01_61/index.html

Presents and demonstrates approaches to interpretation and combination of available data at the well field at the Mirror Lake, New Hampshire fractured-rock hydrology research site. Authors state that these types of studies are needed to facilitate the development of accurate predictive models of ground-water flow and solute transport.

Dee, N. and S. Austin. (1992). Community Wellhead Protection Programs. Oklahoma State University, Cooperative Extension Services. F- 890. 6 p.
http://www.agweb.okstate.edu/pearl/wqs/f-890.pdf

Earle, R. (1994) Modeling Recovery Well Capture Zones in a Fractured Bedrock Aquifer: An Application of the Analytic Element Method. Ground Water 32(5): 850-851.

The analytic element program SLAEM was used to model the capture zones of several hypothetical recovery well configurations in a fractured rock aquifer underlying an industrial site in southeastern Pennsylvania. SLAEM was used to model ground water flow in this fractured bedrock aquifer which encompasses a heavily fractured bedrock sink and is overlain by and in good hydraulic communication with a saturated overburden.

Erdmann, J.B. (2000) On Capture Width and Capture Zone Gaps in Multiple-Well Systems. Ground Water 38(4): 497-504.

Capture zone delineations are fundamental to designing and evaluating the performance of well systems used to capture contaminated ground water. Localized ground water level observations in practice cannot usually define a well system's capture zone, thus calculations based on ground water flow models are essential. Steady-state capture zones for multiple-well systems in uniform background flow are analyzed in the context of the horizontal flow idealization. All well lines perpendicular to background flow, even with irregular spacings and flow rates, are gradientwise-symmetric, as are many other configurations. A gradientwise-symmetric system's center capture width is independent of the number of wells and of their particular placement and spacing. At critical spacing, capture zone gaps are incipient between two center wells, or the center well and two adjacent wells, where contaminant concentrations are usually maximum.

Faybishenko, B.A., I. Javande, and A. Witherspoon. (1996) Hydrodynamics of the Capture Zone of a Partially Penetrating Well in a Confined Aquifer. International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts 33(1): 8A.

A new semianalytic method that can be used in determining the geometry of the capture zone for steady state flow to a partially penetrating well that is screened from the top (or from the bottom) of a confined aquifer has been developed. By combining the velocity potentials for flow to the well with that for the regional flow field, a three-dimensional velocity potential that can be used in determining the complete geometry of the capture surface has been developed.

Feyen, L., K.J. Beven, F. De Smedt, and J. Freer. (2001) Stochastic capture Zone Delineation Within the Generalized Likelihood Uncertainty Estimation Methodology: Conditioning on Head Observations. Water Resources Research 37(3): 625-638.

A stochastic methodology to evaluate the predictive uncertainty in well capture zones in heterogeneous aquifers with uncertain parameters is presented. The approach is based on the generalized likelihood uncertainty estimation methodology. Using inverse particle tracking, a capture zone is determined which is assigned the likelihood calculated for that particular simulation. Results are presented for a hypothetical test case and different likelihood definitions used in the conditioning process. The results show that the delineated capture zones are most sensitive to the mean hydraulic conductivity and the variance, whereas the integral scale of the variogram is the parameter with the smallest influence. For all likelihood measures the prior uncertainty is reduced considerable by introducing the observation heads, but the reduction is most effective for the very selective likelihood definition. The method presented can be used in real applications to quantify the uncertainty in the location and extent of well capture zones when little or no information is available about the hydraulic properties, through the conditioning on head observations.

Forster, C.B., T.E. Lachmar, and D.S. Oliver. (1997) Comparison of Models for Delineating Wellhead Protection Areas in Confined to Semiconfined Aquifers in Alluvial Basins. Ground Water 35(4):689-697. USDA # NAL Call #: TD403.G7.

This study compares 250-day and 15-year time-of-travel (TOT) capture zones computed in a confined to semiconfined aquifer system in an alluvial basin using semianalytical and two- and three-dimensional numerical ground-water flow models, and evaluates the relative importance of several sources of uncertainty, such as aquifer hydraulic conductivity, aquitard leakage, vertical transit time, hydraulic gradients, transient pumping effects, well interference, and three-dimensional aquifer geometries.

Franke, O.L, T.E. Reilly, D.W. Pollack, and J.W. LaBaugh. (1998) Estimating Areas Contributing Recharge to Wells: Lessons from Previous Studies. US Geological Survey Circular 1174. Retrieved October 22, 2001 from the World Wide Web: http://water.usgs.gov/ogw/pubs/Circ1174/

This report provides a brief review of selected concepts, assumptions, and uncertainties related to estimating areas contributing recharge to wells. Topics include ground-water flow modeling, time of travel, and the effects of changing hydrologic conditions and well-screen locations and pumping rates on contributing areas. Individually authored studies are used as examples.

Frederick, K.D. (2002) Subdivision Development in Fractured and Other Sensitive Hydro-geologic Settings: Wyoming's Requirements for Assessments and On-Site Wastewater System Performance. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 19-22.

Goode, D.J. and L.A. Senior. (2000) Simulation of Aquifer Tests and Ground-water Flowpaths at the Local Scale in Fractured Shales and Sandstones of the Brunswick Group and Lockatong Formation, Lansdale, Montgomery County, Pennsylvania. U.S. Geological Survey Open-File Report 00-97, 46 pp. Retrieved from the World Wide Web January 15, 2002 at: http://pa.water.usgs.gov/reports/ofr00-97/

Griswold, W.J. (1991) A Practical Approach to Wellhead Protection in a Fractured Bedrock Aquifer. Proceedings of the Focus Conference on Eastern Regional Ground Water Issues (October 29-31, 1991, Portland, Maine [Ground Water Management Book 7]) : 331-344

An approach to delineating wellhead protection areas (WHPAs) in fractured bedrock aquifers using Time of Travel (TOT) criteria is presented. Based on work conducted on an EPA-sponsored project in Dover, NH, a practical step-by-step methodology is offered that uses standard hydrogeological techniques. Estimated costs for the delineation process are provided.

Griswold W.J., J.H. Vernon, and B.A. Moore. (1990) Developing a Wellhead Protection Area and Monitoring Strategy for a Fractured Bedrock Aquifer, Dover, New Hampshire. Proceedings of the Focus Conference on Eastern Regional Ground Water Issues; October 17-19, 1990; Springfield, Massachusetts (Ground Water Management Book 3) : 131-145.

A wellhead protection area is delineated and a ground water quality monitoring network is designed for a supply well development site in a fractured bedrock aquifer in Dover. A combination of techniques is used in the delineation process, including surficial and bedrock geologic mapping, lineament and structural analysis, borehole and surface geophysics, aquifer testing, and dye tracing. The wellhead protection area is a rectangle with long axis parallel to a prominent northeast-oriented geologic and geophysical trend. Ambient trend and source assessment monitoring strategies (for spills, road salt, radon) are discussed.

Guadagnini, A., and S. Franzetti. (1999) Time-related Capture Zones for Contaminants in Randomly Heterogeneous Formations. Ground Water 37(2): 253-260.

The effect of randomly varying hydraulic conductivity on the spatial location of time-related well capture zones for a nonreactive tracer in a confined aquifer with uniform base flow was studied. A numerical Monte Carlo procedure was used in conjunction with fast Fourier transform-based spectral methods. Various degrees of domain heterogeneity were considered, and stability and accuracy of the numerical procedure were examined. A simple analytical model that extends the deterministic capture-zone model for uniform media is derived.

Haitjema, H., and A. Ceric. (2000) Step-wise Capture Zone Delineation: from Circles to Cells. Midwest Ground Water Conference, 45th Annual, October 17-19, 2000, Columbus, Ohio. p.52.

A dimensionless time of travel parameter was developed to serve as the basis for a number of new simple capture zone delineation methods. These include calculated fixed radius circles and a simple boat shaped capture zone to approach a well in a uniform flow time of travel capture zone. The analytic element code, GFLOW 2000, and MODFLOW were used.

Hers, I., and R. Zapf-Gilje. (1998) Canadian Consortium Research Project - Field Evaluation of Soil Gas Transport to Indoor Air Pathway. Proceedings of the 1998 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation; November 11-13, 1998, Houston, Texas: 251-266

The field study was conducted at a former petrochemical plant near delta, British Columbia. Study methods included extensive delineation of the residual NAPL hydrocarbon concentrations at source, detailed vertical profiling of soil properties and vadose zone hydrocarbon, oxygen, carbon dioxide, and methane concentrations in soil gas. Regular monitoring was used to assess the effect of seasonal changes on soil gas fate and transport. A conceptual model for the vadose zone processes was developed.

Hodgins, M., Lazarus, J., and M. Chudnoff. (2002) Groundwater-Surface Water Communication in Fractured Crystalline Bedrock Aquifer near Red River Pass, Colfax County, New Mexico. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 179-184.

Horsley, S.W. (1990) Water Resources Management Plan for Nantucket Island, Massachusetts - a Case Study. Proceedings of the Focus Conference on Eastern Regional Ground Water Issues; October 17-19, 1990; Springfield, Massachusetts (Ground Water Management Book 3) :3-20.

> To address the threats of both existing and future potential land uses to the ground water quality on the island of Nantucket, a comprehensive water resources management strategy was prepared. The strategy included delineation of critical water resources protection zones and the development of specific land use controls. Utilizing measurements from observation wells, surface gauges, and ground penetrating radar, a water table map was prepared and used to determine ground water flow directions and to map contributing areas to ponds and estuaries. Zones of contribution to public supply wells and an aquifer recharge zone were delineated. Ultimately, four water resource management areas were mapped. Recommended land use controls are presented.

Horton, Jr., J.W., Geddes, Jr., D.J., Chapman, M.J., and C.C. Daniel, III. (2002) Investigating the Influence of Geologic Factors on Ground Water in the Southern Appalachian Piedmont, Reidsville, North Carolina. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 39.

Hsieh, P.A., W. Wingle, and R.W. Healy. (2000) VS2DI - A Graphical Software Package for Simulating Fluid Flow and Solute or Energy Transport in Variably Saturated Porous Media. U.S. Geological Survey Water-Resources Investigations Report 99-4130. Retrieved November 1, 2001 from the World Wide Web:
ftp://water.usgs.gov/pub/software/ground-water/vs2di/doc/vs2di.pdf

> This report provides an overview of the features and capabilities of the VS2DI software package. VS2DI simulates flow and transport in variably saturated porous media in one or two dimensions using cartesian or radial coordinate systems.

Hudak, P.F. (1995) Effective Porosity of Unconsolidated Sand: Estimation and Impact on Capture Zone Geometry. International Journal of Rock Mechanics and Mining Sciences 32(4): 160A.

> Effective and total porosity were measured for three sand samples, and a computer model was used to evaluate the impact of the effective porosity (ne) on the geometry of a groundwater capture zone. The results of this study suggest that: 1) a simple permeameter and vacuum pump apparatus can facilitate the estimation of effective porosity for unconsolidated sands, 2) the magnitude of effective porosity is close to that of total

porosity for unconsolidated sand, and 3) accurate estimates of effective porosity are important for modeling the remediation of contaminated groundwater with capture zones.

Hunt, R.J., J.J. Steuer, M.T. Mansor, and T.D. Bullen. (2001) Delineating a Recharge Area for a Spring Using Numerical Modeling, Monte Carlo Techniques, and Geochemical Investigation. Ground Water 39(5): 702-712.

Recharge areas of spring systems can be hard to identify, but they can be critically important for protection of a spring resource. A recharge area for a spring complex in Southern Wisconsin was delineated using a variety of complementary techniques. Two-hundred model runs used uniformly distributed, randomly sampled, horizontal hydraulic conductivity values with the range given by the TMR optimized values and the previously constructed regional model. A probability distribution of particles captured by the spring, or a "probabilistic capture zone," was calculated from the realistic Monte Carlo results (136 runs of 200). In addition to portions of the local surface watershed, the capture zone encompassed areas outside of the watershed – demonstrating that the ground watershed and surface watershed do not coincide. Analysis of water collected from the site identified relatively large contrasts in chemistry, even from springs withing 15 m of one another. The difference in chemistry was attributed to distinctive bedrock geology as demonstrated by overlaying the capture zone derived from numerical modeling over a bedrock geology map for the area. This finding gives additional confidence to the capture zone calculated modeling.

Indiana Department of Environmental Management. Indian Wellhead Protection Program. Drinking Water Branch, Groundwater Section. Retrieved from the World Wide Web May 6, 2002: http://www.ai.org/idem/owm/dwb/Wellhead/whpp/index2.html

Jacobson, E., R. Andricevic, and J. Morrice. (2002) Probabilistic Capture Zone Delineation Based on an Analytic Solution. Ground Water 40(1): 85-95.

Jarvis, T., Yonkee, A., and M. Matyjasik. (2002) Sustainability of Fractured Bedrock Aquifers, Implications for Growth Management Policy, Summit County, Utah. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 40.

Javandel, I., and C-F Tsang. (1986) Capture-Zone Type Curves: A Tool for Aquifer Cleanup. Ground Water 24(5): 616-625.

Currently a common method of aquifer cleanup is to extract the polluted ground water and, after reducing the concentration of contaminants in the water below a certain level, the treated water is either injected back into the aquifer, or if it is environmentally and economically feasible, released to a surface-water body. The proper design of such an operation is very important, both economically and environmentally. In this paper a method is developed which can assist in the determination of the optimum number of pumping wells, their rates of discharge and locations, such that further degradation of the aquifer is avoided.

Jensen, M.E., Lowe, M., and M. Wireman. (1997) Investigation of Hydrogeologic Mapping to Delineate Protection Zones Around Springs: Report of Two Case Studies. EPA Office of Research and Development EPA/600/SR-97/023. Available on the World Wide Web at: http://www.epa.gov/ada/download/project/prot_zon.pdf

This report summarizes the research project using hydrogeologic mapping methods to identify geologic and hydrologic features that control ground water flow to springs in an effort to aid in delineating protection zones. The report discusses results from two case studies and a general methodology for applying these techniques to delineation of protection zones around springs.

Johnson, C.D., and J.R. Kastrinos. (2002) Use of Geophysical, Hydraulic, and Geochemical Methods to Develop a Site Conceptual Ground Water Flow Model in Connecticut. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 79.

Kacimov, A.R. (2000) Analytic Solution for Transient Flow into A Hemispherical Auger Hole. Journal of Hydrology 228(1-2): 1-9.

An explicit analytic solution for a transient groundwater flow to an auger hole of hemispherical shape is found on the base of ideas and under the same assumptions as in the original paper of Kirkham and van Bavel (1948) Theory of seepage into auger holes, Soil Sci. Soc. Am. Proc., 13, 75-82. The Legendre polynomial expansions are used to solve the Laplace equation with a combination of seepage face and equipotential conditions along the hole contour. A type curve for increasing water level in an initially empty hole is plotted, which allows for a fast determination of the hydraulic conductivity from the observation of filling of a small hole tapping a shallow water table. Time-decreasing total flow rates, velocities, particle trajectories, a capture zone of the hole are calculated using the Wolfram software.

Kilpatrick, F.A. and K.R. Taylor. (1986) Generalization and applications of tracer dispersion data. Water Resources Bulletin 22(4):537-548.

Kizer, M.A. (No Date) Irrigation Wellhead Protection. Oklahoma State University, Cooperative Extension Services. F-1516. 4 p.

Kraemer, S.R., and D.S. Burden. (1992) Capture Zone Delineation Using the Analytic Element Method: A Computer Modeling Demonstration for the City of Hays, Kansas. Proceedings of the Solving Ground Water Problems with Models Conference (February 11-13 1992, Dallas, Texas [Ground Water Management Book 9]): 697.

This poster will guide the participant through the step-wise building of an analytic element model as a tool for the delineation of wellhead protection areas. The model will be constructed to assist in delineation of time-of-travel based capture zones about the wells of the city of Hays, Kansas. The flow problem is first solved within its regional context, with linesinks representing the rivers and reservoirs. The graphical presentation of results allows interactive and visually based calibration of the solution. Then the local scale flow problem is solved, requiring the model to account for additional complexity (i.e., line doublet to demarcate the abrupt hydraulic conductivity transition between the alluvium and the shale). Time-of-travel based capture zones are solved by reverse particle tracking from the pumping wells.

Kraemer, S.R., H.M. Haitjima, and V.A. Kelson. (2000) Working with W*h*AEM2000. Source Water Assessment for a Glacial Outwash Wellfield, Vincennes, Indiana. U.S. EPA. EPA/600/R-00/022.

This document introduces the use of the ground water geohydrology computer program W*h*AEM2000, a public domain, ground-water flow model designed to facilitate capture zone delineation and protection area mapping in support of the State's Wellhead Protection Programs and Source Water Assessment Planning for public water supplies in the U.S. Program operation and modeling practice is covered in a series of progressively more complex representations of the wellfield tapping a glacial outwash aquifer for the city of Vincennes, Indiana. W*h*AEM2000 provides an interactive computer environment for design of protection areas based on radius methods, well in uniform flow solutions, and geohydrologic modeling methods. Protection areas are designed and overlaid upon USGS Digital Line Graph or other electronic base maps. Base maps for a project can be selected from a graphical index map for the State. Geohydrologic modeling for steady pumping wells, including the influence of hydrological boundaries, such as rivers, recharge, and no-flow contacts, is accomplished using the analytic element method.

Kreitler, C.W. and R.K. Senger. (1991) Wellhead Protection Strategies For Confined-Aquifer Settings. EPA 5709-91-008.

Kuniansky, E.L., L. Fahlquist, and A.F. Ardis. (2001) Travel Times Along Selected Flow Paths of the Edwards Aquifer, Central Texas. *In*: U.S. Geological Survey Karst Interest Group Proceedings, Eve Kuniansky (Editor). U.S. Geological Survey Water-Resources Investigations Report 01-4011. Retrieved November 2, 2001 from the World Wide Web: http://water.usgs.gov/ogw/karst/kigconference/elk_traveltimes.htm

Flow-path travel times in the structurally controlled, karstic Edwards aquifer were estimated using simulated ground-water levels obtained from a finite-element model. Includes a description of the limitations of the model and flow path analysis.

LaFave, J.I., Patton, T.W., Smith, L.N., and C.A. Carstarphen. (2002) A Fractured Bedrock and Deep Basin-Fill Aquifer System in the Kalispell Valley, Northwest Montana. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 27-31.

Landmeyer, J.E. (1994) Description and Application of Capture Zone Delineation for a Wellfield at Hilton Head Island, South Carolina, WRI 94-4012. U.S. Geological Survey, Colombia, SC. p. 33.

Linsky, R.B. (1998) Source Water Assessment and Protection 98: A Technical Conference April 28-30, 1998, Dallas, Texas; Sponsored by National Water Research Inst, US Environmental Protection Agency, and US Geological Survey; Cosponsors Include National Ground Water Assoc. 347 p.

> The conference brought together people working on issues identified within the "State Source Water Assessment and Protection Programs Guidance" published by the US EPA in August, 1997. The methodologies developed by states and municipalities for area delineation, data management, monitoring, and measuring effectiveness are discussed.

Lyford, F.P., and G.J. Walsh. (2002) Hydrogeologic Framework and Simulated Contributing Areas for Three High-Yield Bedrock Well Sites in Metamorphic Rocks of Eastern Massachusetts. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 24-25.

> Studies of three bedrock aquifers in eastern Massachusetts were designed to provide insights about contributing areas to public-supply wells completed in metamorphic rocks and information needed by regulators to confidently delineate well-head protection zones. Numerical three-dimensional models, constructed on the basis of detailed geologic mapping and aquifer-test data, were used to delineate contributing areas to wells and variations that result from alternative but plausible model characteristics.

Mack, T.J., Degnan, J.R., and R.B. Moore. (2002) Regional Simulation of Ground-Water Flow in a Fractured Bedrock Aquifer, New Hampshire. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 147-151.

> This study evaluates a regional bedrock aquifer system that extends from New Hampshire's rapidly growing seacoast to upland areas 25 miles inland. Objectives of the study were to: 1) characterize the regional ground-water flow system and estimate fresh ground-water discharge to Great Bay, New Hampshire; and 2) examine the use of ground-water-flow simulation to assess fresh ground water resources in the region.

Marquis, S.A., Jr. (1992) The Delineation of Time-Related Capture Zones in Groundwater Remediation Investigations using a Semi-Analytical Flow Model. The Proceedings of the Sixth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and

Geophysical Methods, May 11-13, 1992, Las Vegas, Nevada (Ground Water Management Book 11): 499-513.

This study provides a simple, cost-effective method for evaluating steady-state and time-related capture zones in ground water remediation investigations using the well head protection area model (WHPA 2.01), a semi-analytical ground water flow (particle tracking) model developed for the US EPA to assist in delineating capture zones of water supply wells in well head protection area studies. The application of the model is strictly valid only for uniform, steady-state, two-dimensional flow through homogenous, isotropic porous media of constant thickness. The advantages and limitations of WHPA 2.01 are discussed. The following computer models and modules were used in the study: AQTESOLV (for analyzing pumping test date), RESSQC (for accounting for the effects of well interference in capture zone analysis), and MWCAP (for verifying that RESSQC output is consistent with known field hydraulic conditions).

Marquis, S.A., Jr., and E. Stewart. (1994) The Delineation of Wellhead Protection Areas in Fractured Bedrock Terrains Using Groundwater Flow Models. Proceedings of the Eighth National Outdoor Action Conference and Exposition on Aquifer Remediation, Ground Water Monitoring, and Geophysical Methods. May 23-24, 1994, Minneapolis, Minnesota: 327-343.

Two case studies are presented in which ground water flow codes were used to delineate wellhead protection areas (WHPAs) for water supply in fractured bedrock terrains. Five-year capture zones were developed for a municipal well field in the fractured carbonate aquifer in Richwood, Ohio, using analytical (CAPZONE/GWPATH), numerical (MODFLOW/MODPATH), and semianalytical (DREAM/WHPA [RESSQC]) models. A numerical ground water flow and particle tracking code (FLOWPATH) was used to delineate 10-year capture zone fro three potential water supply wells in a fractured granitic bedrock aquifer at a real estate parcel in Moreno Valley, California. The objective of computer modeling was to select an appropriate location for a water supply well in which the predicted 10-year capture zone did not intersect a hydrocarbon plume present in the ground water at a former fuel dispensing facility located upgradient of the parcel. The fundamental differences between analytical, numerical, and semianalytical models; and the general advantages and limitations of computer models in wellhead protection area delineation are addressed. A figure is included which depicts the relationships between zone of influence, time-related zone of capture (zone of transport), and steady state capture zone (zone of contribution) around a pumping well. The digital model AQTESOLV was used for pump test analysis.

McDonald, Michael G., and Arlen W. Harbaugh. (1988) A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. (MODFLOW) *In:* Techniques of Water-Resources Investigations of the United States Geological Survey, Chapter A1. Available on the World Wide Web at: http://water.usgs.gov/pubs/twri/twri6a1/html/pdf.html

This report presents a finite-difference model that simulates flow in three dimensions, and its associated modular computer program. It includes detailed explanations of physical and mathematical concepts on which the model is based and an explanation of how those concepts are incorporated in the modular structure of the computer program.

McElwee, C.D. (1991) Capture Zones for Simple Aquifers. Ground Water 29(4): 587-590.

Capture zones showing the area influenced by a well within a certain time are useful for both aquifer protection and cleanup. If hydrodynamic dispersion is neglected, a deterministic curve defines the capture zone. Analytical expressions for the capture zones can be derived for simple aquifers. The presented program is written in fortran and has been used in a variety of computing environments. No graphics capability is included with the program; it is assumed the user has access to a commercial package. Because this program deals with simple aquifers, the results rarely will be the final work in a real application. However, the program is useful as a first phase in developing wellhead protection or aquifer cleanup schemes.

McFarland, E. Randolph. (1998) Design, Revisions, and Considerations for Continued Use of a Ground-Water-Flow Model of the Coastal Plain Aquifer System in Virginia. U.S. Geological Survey Water Resources Investigations Report 98-4085. Retrieved November 7, 2001 from the World Wide Web: http://va.water.usgs.gov/online_pubs/WRIR/98-4085/g-wfmcpasys_va.html

A digital numerical model of the ground-water-flow system in the large and complex Virginia Coastal Plain was constructed as part of the Regional Aquifer System Analysis program of the USGS and subsequently revised based on reinterpretations of the hydrogeologic framework.

Meinardus, H.W., V. Dwarakanath, M. Fort, R.E. Jackson, M. Jin, J.S. Ginn, and G.C. Stotler. (1999) Delineation of a DNAPL Source Zone with Partitioning Interwell Tracer Tests. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation; November 17-19, 1999, Houston, Texas: 79-85.

Since the late 1960s, DNAPL has migrated from trenches at the hill AFB, Utah, through the alluvium and pooled in depressions in the underlying clay aquiclude. In 1996, it was discovered that this clay aquiclude was part of a buried paleochannel that was deeply incised into the underlying clay. Four partitioning interwell tracer tests (PITT) were used to delineate the source zone. Initial tasks included hydrostrategraphic delineation resulting in a divergent-flow line drive well field design. Laboratory work and utchem simulations were used to characterize the geosystem and design the PITT. The PITT results provided a definitive estimate of the amount of DNAPL remaining in the source zone.

Misqueitta, N., J. Mack, and D. Kerschner. (1994) Optimization of Ground Water Capture Zones Using an Intelligent Control Process. Ground Water 32(5): 855-856.

An intelligent control process termed an intelligent pump-and-treat (IPT) control process automates pump-and-treat ground water recovery systems to maintain constant control of extraction well capture zones during remedial activities. Components and advantages of the IPT control process are listed.

Moench, A.F. and P.M. Barlow. (2000) Aquifer Response to Stream-stage and Recharge Variations, I. Analytical Step-response Functions. Journal of Hydrology 230:192-210. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/abstracts.00.html#moench

Laplace transform step-response functions are presented for various homogeneous confined and leaky aquifer types and for anisotropic, homogeneous unconfined aquifers interacting with perennial streams.

Moench. A.F., S.P. Garabedian, and D.R. LeBlanc. (2001) Estimation of Hydraulic Parameters from an Unconfined Aquifer Test Conducted in a Glacial Outwash Deposit, Cape Cod, Massachusetts. U.S. Geological Survey Professional Paper 1629. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/pubs/pp/pp1629/pdf/pp1629ver2.pdf

An aquifer test conducted in a sand and gravel, glacial outwash deposit on Cape Cod, Massachusetts was analyzed by means of a model for flow to a partially penetrating well in a homogeneous, anisotropic unconfined aquifer. Authors suggest that because of the nearly ideal conditions and high data quality this aquifer test can be used as a standard against which other tests can be compared.

Moench, A.F. (1997) Flow to a Well of Finite Diameter in Homogeneous, Anisotropic Water Table Aquifer. Water Resources Research 33(6):1397-1407.

Moench, A.F. (1995) Combining the Neuman and Boulton Models for Flow to a Well in an Unconfined Aquifer. Ground Water 33(3):378-384.

Moore B.A., A. H. Cathcart, and S.C. Danos. (1990) Littleton, Massachusetts Wellhead Protection and Monitoring Strategy. Proceedings of the Focus Conference on Eastern Regional Ground Water Issues; October 17-19, 1990; Springfield, Massachusetts (Ground Water Management Book 3) : 47-67.

Five years before enactment of the wellhead protection program in1986, Littleton, Massachusetts, researched and adopted a comprehensive aquifer and watershed management protection program. This paper documents the technical development of Littleton's protection program, focusing on the wellhead protection area delineation process and subsequent monitoring strategies. The methods used to delineate aquifer recharge protection areas are discussed including: hydrogeologic and geophysical mapping, analytical solutions, and numerical ground water flow modeling. The Prickett-Longquist aquifer simulation model (plasm) was used to assist in delineating aquifer protection zones.

Moore, R.B., Schwarz, G.E., and S.F. Clark, Jr. (2002) Site and Well Characteristics Related to Well Yields in the Fractured-Bedrock Aquifer of New Hampshire. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 37.

The USGS investigated the yields of wells in New Hampshire's bedrock aquifer. The data set used for the study was compiled by the State of New Hampshire, and includes 20,308 accurately located wells with information on yield, depth, and construction. The analysis produced a statewide GIS grid of well-yield probablities, which may be used to assess potential water supplies and characterize bedrock aquifers for the development of regional ground-water flow models.

Mull, D.S., T.D. Liebermann, J.L. Smoot, and L.H. Woosley, Jr. (1988) Application of Dye-Tracing Techniques for Determining Solute-Transport Characteristics of Ground Water in Karst Terranes. EPA 904/6-88-001. Retrieved from the World Wide Web January 15, 2002 at: http://www.karstwaters.org/files/dyetracer.pdf

The purposes of this manual are to provide a review of the hydrogeology of karst terranes, summarize concepts and techniques for dye tracing, and describe and demonstrate the application of dye-trace data to determine solute-transport characteristics of ground-water in karst terranes. The manual was prepared in support of the Wellhead Protection Program pursuant to the 1986 Amendments to the Safe Drinking Water Act.

Mull, D.S., J.L. Smoot, and T.D. Liebermann. (1988) Dye Tracing Techniques Used to Determine Ground-water Flow in a Carbonate Aquifer System near Elizabethtown, Kentucky. U.S. Geological Survey Water-Resources Investigations Report 87-4174, 95 pp.

Musa, M., and M.W. Kemblowski. (1996) Transient Capture Zone for a Single Well. Ground Water 34(1): 168-170.

A method was developed that combines the analytical solution for the steady state capture zones and transient velocity field with particle tracking. Using the particle trajectories, and effective capture zone can be estimated. No contaminant outside this zone at the start of pumping can be captured by the well.

National Research Council. (1999) Conceptual Models of Flow and Transport in the Fractured Vadose Zone. Panel on Conceptual Models of Flow and Transport in the Fractured Vadose Zone. Workshop 1999. National Academy Press, Washington, DC.

Nelson M.E., and J.D. Witten. (1990) Delineation of a Wellhead Protection Area in a Semi-confined Aquifer - Manchester, Massachusetts. Proceedings of the Focus Conference on Eastern Regional Ground Water Issues; October 17-19, 1990; Springfield, Massachusetts (Ground Water Management Book 3) : 31-45.

> A comprehensive water resources management plan was prepared for the Town of Manchester with the goal of protecting the water quality in the Lincoln street well, the only source of potable drinking water located in the town. The management plan focused on two main objectives: a detailed hydrogeologic delineation of the zone of contribution to the public supply well, and the development of a water resources protection strategy to protect the quality of the sources of water entering the wellhead. Results of pumping tests are reported. Modeling assumptions and results are discussed, and the resulting zones of contribution are mapped. The digital model MODFLOW was used in the study. Regulatory and non-regulatory recommendations for ground water protection are outlined.

Nelms, D.L., Plummer, N., and E. Busenberg. (2002) Susceptibility of Fractured-Rock Aquifers in Virginia Based on Ground-Water Dating Techniques. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 51.

Ohio EPA. (2000) Summary of Wellhead Protection Plans and Review Criteria. Wellhead Protection Program. 23 p. Retrieved May 6, 2002 from the World Wide Web: http://www.epa.state.oh.us/ddagw/pdu/review.pdf

Ohio Environmental Protection Agency. (1999) Source Water Assessment and Protection Program. Divisions of Drinking and Ground Waters, and Surface Water.

> Ohio's Source Water Assessment and Protection (SWAP) program is an innovative program to protect) Ohio's streams, rivers, lakes, reservoirs, and ground waters used for public drinking water from future contamination. Building on existing environmental assessment and protection programs, SWAP will identify drinking water protection areas and provide information on how to reduce the potential for contaminating the waters within those areas.

Orzol, L.L., and M. Truini. (1999) Evaluation of Factors that Influence Estimated Zones of Transport of Six Municipal Wells in Clark County, Washington. Water-Resources Investigations, WRI 97-4224. U.S. Geological Survey, Portland, OR.: 65.

Paillet, F.L., and W.H. Pedler (1996) Integrated Borehole Logging Methods for Wellhead Protection Applications. May, J., and K.E. Kolm (eds.) Advanced Techniques for Solving Groundwater Contaminant Problems. Engineering Geology. 42(2-3): 155-165.

Pekas, B.S. (1992) Capture-Zone Geometry Calculations with Spreadsheet Programs. Proceedings of the Solving Ground Water Problems with Models Conference (February 11-13, 1992, Dallas, Texas [Ground Water Management Book 9]: 653-666.

A pair of spreadsheet programs are presented to determine the theoretical capture zone geometry. The data requirements for the programs include the hydraulic parameters and properties of the aquifer system (confined or unconfined), pumping conditions, and desired radial distances from a pumping well. The programs will calculate the theoretical capture zone geometry including potential drawdown impacts, ground water elevations, flow velocity fields, ground water divide distances, and travel time requirements for an anticipated pumping scheme. The program can also graphically display the resulting data as distance related profiles of the capture zone geometry to assist in understanding the hydraulic relationship between the well and the aquifer system. Estimating the capture zone of a pumping well is necessary to evaluate the potential effectiveness (physical and financial) or remedial actions. Using these programs, a ground water scientist or engineer can efficiently perform multiple analytical calculations for various hydrogeologic and pumping scenarios on simple aquifers. These calculations should, at a minimum, include the end members of hydrogeologic conditions at the site to account for potential uncertainties. Thus, the programs allow selection of an initial pumping scenario which satisfies the most remedial objectives of the study.

Person M., J.Z. Taylor, and S.L. Dingman. (1998) Sharp Interface Models of Salt Water Intrusion and Wellhead Delineation on Nantucket Island, Massachusetts. Ground Water 36(5):731-742

A sharp-interface model is used to assess the impact of projected increases in pumping from Wyers Valley and proposed state forest municipal wellfields on Nantucket Island ground water resources. The calculated model results suggest that salt water will invade the deep (32 m) production well at Wyers Valley wellfield by 2014. Calculated wellhead delineation zones were found to be most sensitive to island geometry and to a lessor extent to the freshwater lens thickness.

Plummer, L.N., E. Busenberg, J.B. McConnell, S. Drenkard, P. Schlosser, and R.L. Michel. (1998) Flow of River Water into a Karstic Limestone Aquifer. 1. Tracing the Young Fraction in Groundwater Mixtures in the Upper Floridan Aquifer near Valdosta, GA. Applied Geochemistry 13:995-1015.

Data on transient tracers and other dissolved substances were investigated as tracers of Withlacoochee River water in the Upper Floridan Aquifer. Groundwater mixing fractions were determined. Error simulation procedures were used to define uncertainties in mixing fractions.

Plummer, L.N., E. Busenburg, S. Drenkard, P. Schlosser, B. Ekwurzel, R. Weppernig, B. McConnell, and R.L. Michel. (1998) Flow of River Water into a Karstic Limestone Aquifer. 2. Dating the Young Fraction in Groundwater Mixtures in the Upper Floridan Aquifer near Valdosta, GA. Applied Geochemistry 13:1017-1043.

> Tritium/helium-3 and chlorofluorocarbon data are used to date the young fraction in groundwater mixtures from a karstic limestone aquifer near Valdosta, GA, where regional paleowater in the Upper Floridan aquifer receives recharge from two young sources - the flow of Withlacoochee River water through sinkholes in the river bed, and leakage of infiltration water through post-Eocene semi-confining beds above the Upper Floridan aquifer.

Plummer, L.N. and L.C. Friedman. (1999) Tracing and Dating Young Ground Water. U.S. Geological Survey Fact Sheet 134-99. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/pubs/FS/FS-134-99/pdf/fs-134-99.pdf

> Overview of how data on concentrations of environmental tracers can be used to trace the flow of young water (water recharged within the past 50 years) and to determine the time elapsed since recharge. Focuses on how this data can be used to define recharge rates, refine hydrologic models of ground-water systems, predict contamination potential, and estimate the time needed to flush contaminants from ground-water systems.

Podgorney, R.K., and R.W. Ritzi Jr. (1997) Capture Zone Geometry in a Fractured Carbonate Aquifer. Ground Water 35(6): 1040-1049.

> A fractured carbonate aquifer was examined that has a transition from porous media type (continuum) flow near the bedrock surface to discrete fracture (noncontinuum) flow at depth. Three depth zones were delineated using a borehole flowmeter, video logs, and pumping tests. These zones were not related to lithologic boundaries, showing that monitoring well design based solely on lithology may be inappropriate in some fractured systems. The geometries of capture zones in this aquifer were determined by combining the field observations with numerical modeling. The capture zone geometries are very complex. The presence of open corehole monitoring wells affected the flow regime under both ambient and pumping conditions. The wells act as short circuits between otherwise isolated fractures and fracture zones. Implications of fracture flow on monitor well design is discussed.

Poeter, E., Thyne, G., McCray, J., Lee, J., and G. VanderBeek. (2002) Low-Cost Data for Characterization & Management of Fractured-Crystalline Aquifers. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 15-18.

> This project couples drill-log data with more sophisticated meteorological, surface water, water quality, isotope, and geophysical data through programs implemented by Jefferson

County, the USGS and graduate students to build a mathematical representation of ground-water flow in the basin that is consistent with field data. The project began in fall of 2001, so the results are preliminary. Eventually, the model will facilitate evaluation of sustainable water use in the basin.

Puls R.W., D.A. Clark, C. Carlson, and J. Vardy. (1994) Characterization of Chromium-contaminated Soils Using Field-portable X-ray Fluorescence. Ground Water Monitoring and Remediation 14(3): 111-115.

A detailed characterization of the underlying and adjacent soils near a chrome plating shop utilized field-portable X-ray Fluorescence (XRF) as a screening tool. XRF permitted real-time acquisition of estimates for total metal content of soils. Detection limits for the XRF instrument used in the study are provided for lead, arsenic, copper, chromium, zinc, iron, cadmium, and barium. Minerals present in soil at the study site are mentioned.

Quinlan, J.F. (1987) Qualitative Water-tracing with Dyes in Karst Terranes. *In*: Practical Karst Hydrogeology, with Emphasis on Groundwater Monitoring (course manual), J.F. Quinlan (Editor). National Water Well Association, Dublin, Ohio, 6:E1-E24.

Raymon, H., K. Hunt, K. Metropulos, M. Bondoc, P. Heider, J. McGinnis, S. Mosher, M. Preston, and M. Proffit. (2000) Technical Approach to Delineating Source Water Protection Areas in Ohio. Midwest Ground Water Conference, 45th Annual, October 17-19,2000, Columbus, Ohio. 53 p.

The delineation method is based on hydrogeologic setting, pump rate, and availability of hydrogeologic data. Delineation methods range from simple calculated fixed radius methods to more complex analytic element models. A variable shape method was developed for small water systems.

Ramanarayanan, T.S., D.E. Storm, M.D. Smolen, and M.A. Kizer. (1992) Comparison of an Analytical Model and a Numerical Model for Delineating Wellhead Protection Areas. Pap-Am-Soc-Agric-Eng. St. Joseph, MI: American Society of Agricultural Engineers, 922036. 15 p.

Ranalli, T., Stevens, M., and K. Bossong. (2002) Water Quality in a Turkey Creek Watershed. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 41.

Ray, B.W. (1992) Wellhead Protection Effects on Agricultural and Rural Areas. American Society of Agricultural Engineers. Paper No. 92-2502/92-2520. 7 p.

Reilly, Thomas. (2001) System and Boundary Conceptualization in Ground-Water Flow Simulation. *In*: Techniques of Water-Resources Investigations of the U.S. Geological Survey Book 3, Application of Hydraulics, Chapter B8. Retrieved October 25, 2001 from the World Wide Web: http://water.usgs.gov/pubs/twri/twri-3_B8/

This report focuses on describing different ways to simulate, in a numerical model, the physical features that act as hydrologic boundaries in an actual ground-water system. The ramifications, benefits, and limitations of each approach are discussed, and descriptions of the representation of boundaries in models for Long Island, New York, and the Middle Rio Grande Basin, New Mexico, illustrate the application of some of the methods.

Reilly, T.E. and D.W. Pollock. (1996) Sources of Water to Wells for Transient Cyclic Systems. Ground Water 34(6):979-988. NAL Call #: TD403.G7.

The thrust of some WHP programs is to protect water supplies by determining the areas contributing recharge to water-supply wells and by specifying regulations to minimize the opportunity for contamination of the recharge water by activities at the land surface. In the analyses of ground-water flow systems, steady-state average conditions are commonly used to simplify the problem and make a solution tractable. However, recharge is usually cyclic in nature, with seasonal cycles and longer term climatic cycles. The effect of these cyclic stresses on the area contributing recharge to walls is quantitatively analyzed for a hypothetical alluvial valley aquifer system that is representative of a large class of ground-water systems that are extensively developed for water supply. This analysis shows that, in many cases, these cyclic changes in the recharge rates do not significantly affect the location and size of the areas contributing recharge to wells. The ratio of the mean travel time to the length of the cyclic stress period appears to be an indicator of whether the transient effects of the cyclic stress must be explicitly represented in the analysis of contributing areas to wells. For the cases examined, if the ratio of the mean travel time to the period of the cyclic stress was much greater than one, then the transient area contributing recharge to wells was similar to the area calculated using an average steady-state condition. However, cyclic stresses on systems. with ratios less than one do have an effect on the location and size of the areas contributing recharge to walls.

Reilly, T.E., and D.W. Pollock. (1995) Effect of Seasonal and Long-term Changes in Stress on Sources of Water to Wells. W 2445. U.S. Geological Survey. P. 25.

The area contributing recharge to a discharging well is that surface area that defines the location of the water entering the ground-water systems at the water table which flows to the well and is eventually discharged from the well. Recharge is usually cyclic in nature, with seasonal cycles and longer term climatic cycles. A hypothetical system is quantitatively analyzed to show that, in many cases, these cyclic changes in the recharge rates apparently do no significantly affect the location and size of the areas contributing recharge to wells.

Reilly, T.E., and D.W. Pollock. (1993) Factors Affecting Areas Contributing Recharge to Wells in Shallow Aquifers. U.S Geological Survey. W 2412. p. 21.

The area contributing recharge to a discharging well is the surface area that defines the location of the water entering the ground-water system at the water table that slows to the well and is eventually discharged from the well. Hypothetical experiments are undertaken to show complexities in the delineation of areas contributing recharge to wells. The main conclusion drawn from the experiments in that in order to understand the cause and effect relations that affect the quality of water derived from wells, the importance and nature of the variability in the ground-water flow system must be considered and accounted for in any efforts to "protect" the water-supply.

Robinson, J.L. (1995) Hydrogeology and Results of Tracer Tests of the Old Tampa Well Field in Hillsborough County, with Implications for Wellhead-protection Strategies in West-central Florida. WRI 93-4171. U.S. Geological Survey, Tallahassee, FL. p. 63.

Rust, C.C. (2002) The Fractured Granite Terrain of Eastern Madera County California: A Ground Water Crisis in Progress. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 24-25.

Schafer, D.C. (1996) Determining 3D Capture Zones in Homogeneous Anisotropic Aquifers. Ground Water 34(4): 628-639.

The integration of drawdowns from point sinks to create line sinks and the differentiation of drawdown with respect to the three coordinate axes provide the basis for a flow field which can bee superimposed upon a particle tracking scheme to simulate the capture and extraction of contaminants. Examples of the numerical simulation show profiles of capture zones around horizontal drains and partially or fully penetrating vertical extraction wells. Capture zones around single and multiple extraction wells are illustrated in three dimensions.

Schlinger, C.M. (2002) Navajo Aquifer Water Supply for Kayenta Community School. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 32-36.

Sepulveda, Nicasio. (2001) Comparisons Among Ground-Water Flow Models and Analysis of Discrepancies in Simulated Transmissivities of the Upper Floridan Aquifer in Ground-Water Flow Model Overlap Areas. *In*: U.S. Geological Survey Karst Interest Group Proceedings, Eve Kuniansky (Editor). U.S. Geological Survey Water-Resources Investigations Report 01-4011. Retrieved November 7, 2001 from the World Wide Web: http://water.usgs.gov/ogw/karst/kigconference/ns_comparisons.htm

Seven ground-water flow models in southwest and south-central Florida were analyzed to identify discrepancies in the simulated transmissivity in model overlap areas.

Shapiro, A.M. (2002) Characterizing Fractured Rock for Water Supply: From the Well Field to the Watershed. In: Fractured-Rock Aquifers 2002, March 13-15, 2002 Denver, Colorado. Pg. 6-9.

Shapiro, A.M. (2001) Characterizing Ground-Water Chemistry and Hydraulic Properties of Fractured Rock Aquifers Using the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT^3). U.S. Geological Survey Fact Sheet FS-075-01. Retrieved November 5, 2001 from the World Wide Web: http://toxics.usgs.gov/pubs/FS-075-01/

> The USGS has a patent pending on BAT^3, portable equipment used to test fractured-rock aquifer properties. This fact sheet describes the capabilities of this equipment.

Shapiro, A.M., P.A. Hsieh, and F.P. Haeni. (1999) Integrating Multidisciplinary Investigations in the Characterization of Fractured Rock. U.S. Geological Survey Toxic Substances Hydrology Program–Proceedings of the Technical Meeting Charleston, South Carolina March 8-12, 1999. Volume 3 of 3–Subsurface Contamination From Point Sources, Water-Resources Investigations Report 99-4018C. Retrieved November 1, 2001 from the World Wide Web: http://toxics.usgs.gov/pubs/wri99-4018/Volume3/SectionG/3801_Shapiro/index.html

> A multiple-method hierarchical approach to characterization in fractured rock is presented.

Sheets, R.A. (1994) Contributing Recharge Areas of Water-supply Wells at Wright-Patterson Air Force Base, Ohio. WRI 94-4231. U.S. Geological Survey, Columbus, OH. p. 35.

Sidauruk, P., A.H-D. Cheng , and D. Ouazar. (1998) Ground Water Contaminant Source and Transport Parameter Identification by Correlation Coefficient Optimization. Ground Water 36(2): 208-214.

> Inverse procedures based on correlation coefficient optimization are developed to locate ground water contaminant sources and to identify transport parameters. For cases involving two-dimensional instantaneous and continuous sources, the inverse formulas are explicit. These procedures allow not only for the delineation of the sampled contaminant plume, but also the tracing and the projection of the plume history.

Silliman, S.E. (2001) Laboratory Study of Chemical Transport to Wells Within Heterogeneous Porous Media. Water Resources Research 37(7): 1883-1892.

> A laboratory flow cell was used to study chemical transport to wells producing water from two realizations of a heterogeneous porous medium. For both realizations, the aquifer was composed of a two-dimensional, lognormally distributed, second-order stationary, exponentially correlated conductivity field. The focus was on the nature of the dispersion observed in the chemical arrival at the pumping well. Results indicate that the

shape and timing of a breakthrough curve at a well producing within a regional flow field may be strongly dependent on the distance of the well from the source.

Silva, G.P., and T.P. Ballestero. (2002) A Numeric Model for Hydraulic Parameters Estimation During Packers Water Sampling in Low Yielding Formations. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 42.

A finite-differences model was developed to estimate hydraulic conductivity and storage coefficient from data taken during the required well purging prior to sampling bedrock wells. A Java Applet for the model is available at www.bbc.unh.edu.

Smart, C.C. (1988) Artificial Tracer Techniques for the Determination of the Structure of Conduit Aquifers. Ground Water 26:445-453.

Spayd, Steven E. (1989) Draft Guidance for Wellhead Protection Area Delineations in New Jersey. New Jersey Geological Survey. Available on the World Wide Web at: http://www.state.nj.us/dep/dsr/wellhead.pdf

This document describes approved wellhead protection and delineation methods in New Jersey. It describes delineation methods and selection, minimum data requirements, and input parameters for delineation models. Methods described include calculated fixed radius, estimated and measured gradient models, and three-dimensional and complex models.

Springer, A.E., and E.S. Bair. (1992) Comparison of Methods Used to Delineate Capture Zones of Wells: Stratified-Drift Buried-Valley Aquifer. Ground Water 30(6): 908-917.

Analytical, semi-analytical, and numerical models of the flow systems in a stratified drift, Buried Valley aquifer were used with particle-tracking/stream-function programs to delineate travel-time-related capture zones of a municipal well field and to assess conceptual errors imposed by requisite assumptions associated with each flow model. Conceptual errors associated with use of the analytical and semi-analytical flow models in this hydrogeologic setting cause their one-year capture zones to be less reasonable than those from the numerical flow model. The following computer models were used in the study: CAPZONE and GWPATH (analytical method), RESSQC (part of WHPA program) and DREAM (semi-analytical method), and MODFLOW and MODPATH (numerical method).

Starn, J.J., Stone, J.R., and R. Mondazzi. (2002) Multiple-scale investigation of contributing areas to wells in fractured rock. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 46.

The USGS conducted an investigation of contributing areas to wells in a fractured rock aquifer at two scales in Connecticut - the well-field and watershed scales. The purpose was to identify techniques to assess source=water areas for pollution prevention. The well-field-scale (hydraulic and geophysical analysis) and watershed-scale information (geologic and DEM analysis) were used in a watershed-scale ground-water -flow model to delineate contributing areas.

Stoessell, R.K. (1997) Delineating the Chemical Composition of the Salinity Source for Saline Ground Waters: an Example from East-central Concordia Parish, Louisiana. Ground Water 35(3): 409-417.

Low temperatures and short reaction times often lead to insignificant water-rock interactions in ground water pollution involving brines. Under these conditions, conservative mixing relations allow delineation of the chemical composition of the source brines for pollution. An example from Concordia Parish was used to illustrate delineation of the source brine chemistry.

Sullivan, E.J., and R. Nava. (1999) Use of Organic and Inorganic Solutes in Tracing Oil-field Salt-water Sources: Delineation of Recent Versus Historic Sources. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation; November 17-19, 1999, Houston, Texas: .331-347.

Salt water from both natural and anthropogenic sources impacts ground and surface water in West Texas. It was hypothesized that differences in water chemistry, including the presence of soluble organic constituents such as benzene, and ratios of major ions and metals can be used to distinguish between old sources and more recent sources. The study area was near the southeastern limit of the Ogallala aquifer. Ground water, surface spring water, and produced water samples were analyzed for dissolved solids, major cations, major anions, and BTEX. The hydrogeology of the site was defined. Sampling location data were entered into a geographic information system database, along with the locations of current and former oil and injection wells, and local springs and surface water bodies. The elevated BTEX zone and the elevated chloride zone were superimposed on the map of well locations using GIS, enabling several oil wells and one former injection well to be targeted for further study for source identification.

Taylor, Charles, J. and Earl A. Greene. (2001) Quantitative Approaches in Characterizing Karst Aquifers. *In*: U.S. Geological Survey Karst Interest Group Proceedings, Eve Kuniansky (Editor). U.S. Geological Survey Water-Resources Investigations Report 01-4011. Retrieved October 26, 2001 from the World Wide Web:
http://water.usgs.gov/ogw/karst/kigconference/cjt_quantitative.htm

This report discusses the advantages and disadvantages to various quantitative approaches for investigating karst aquifers.

Taylor, J.Z., and M. Person. (1998) Capture Zone Delineations on Island Aquifer Systems. Ground Water 36(5): 722-730.

An assessment was made of the effects of variable-density ground water flow on capture zones for pumping wells on islands and the ability of numerical and analytical methods to account for these effects. Sensitivity studies are completed using computer models to identify the influence of variable-density flow on computed time-related zones of contribution to pumping wells. Quantitative results indicate that the size and shape of the capture zone is sensitive to the natural geometry of the fresh water lens and the effects of freshwater: saltwater upcoming. The study results serve to caution model users of the limitations inherent in using analytical methods to compute capture zone delineations for island aquifers.

Taylor, R.G., Risley, D., Staufer, S., and B. Allred. (2002) Idaho's On-going Source Water Assessment Program and Transition to Drinking Water Protection in the Snake River Basalts of Twin Falls County. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 47-50.

Tiedeman, C.R. and P.A. Hsieh. (1999) Analysis of an Open-Hole Aquifer Test in Fractured Crystalline Rock. U.S. Geological Survey Toxic Substances Hydrology Program–Proceedings of the Technical Meeting Charleston South Carolina March 8-12, 1999. Volume 3 of 3–Subsurface Contamination From Point Sources, Water-Resources Investigations Report 99-4018C. Retrieved November 1, 2001 from the World Wide Web: http://toxics.usgs.gov/pubs/wri99-4018/Volume3/SectionG/3813_Tiedeman/index.html

A multiple-well open-hole aquifer test was conducted in fractured crystalline rock underlying the well field at the Mirror Lake, New Hampshire fractured-rock hydrology research site. Study compares effectiveness and discusses limitations of an open-hole test and leaky-aquifer and double porosity analytical models.

Tolman, A. L., G.E. Lipfert, M.C. Loiselle. (2000) Maine's Wellhead Delineation Project. Proceedings of the 2000 Ground Water Protection Council Annual Forum, September 24-27, 2000, Ft. Walton Beach, Florida: 155-166.

Maine's wellhead protection program permits public water systems to utilize the calculated fixed radius method to approximate the protection area for a well. The current project was initiated to assess the susceptibility to contamination of every public water source (beginning with a delineation). Delineations were performed using existing, pump test, and operating data. ARC-INFO coverages of hydrologic, topographic, and geologic data provide the framework for MODFLOW and MODPATH models of each district's sources. Numerical models were developed for each aquifer to allow simulation of boundary conditions and assist in determining the recharge areas to indicate the needed protection zone.

Tolman, A.L., M.C. Loiselle, and P. Hunt. (1999) Maine's Wellhead Delineation Project. Ground Water Supply Issues in the next Century, 1999 Abstract Book, NGWA National Convention and Exposition, December 3-6, 1999, Nashville: 90-91.

A project to improve wellhead protection delineations for more than 80 large municipal suppliers utilizing sand and gravel aquifers is underway in Maine. Its wellhead protection program permits public water systems to utilize the calculated fixed radius method to approximate the protection area for a well. Areas contributing significant recharge to the municipal wells are being delineated. The models, ARC-INFO, MODFLOW, and MODPATH, are being used.

Traylor, R.L., and R. Nagel. (1999) Comparison of Delineation Methods Used for Calculating a Zone of Contribution to a Water Supply Well. Pacific Northwest Focus Ground Water Conference, February 17-19, 1999, Portland, Oregon.: 20.

Source protection programs are based on a simple volumetric calculation based on depth of the well and pumping rate. This Modified Calculated Fixed Radius Method (MCFR) was compared to computer modeling - partial tracking (modeling) in order to identify the precision of the MCFR. Multiple input variables were evaluated. Modeling showed that the greatest deviation from the MCFR occurs when ground water gradients are greater than 0.004 feet per foot. Caution is urged in source protection programs where gradients are greater than 0.002 feet per foot.

University of Idaho. BMPs for Wellhead Protection. College of Agriculture, Cooperative Extension System. Retrieved May 6, 2002 from the World Wide Web: http://www.uidaho.edu/wq/wqbr/wqbr30.html

Over 90 percent of the drinking water consumed in Idaho is supplied by groundwater. This resource is vital to homeowners and industry as well as Idaho's agricultural community. Best management practices (BMPs) for wellhead protection have been and are becoming more important.

Urban Institute. (1992) *Suggestions for State and Local Groundwater Protection Programs. Encouraging Local Groundwater Protection Programs.* Volume II.

Urban Institute. (1992) *Suggestions for State and Local Groundwater Protection Programs: Providing Information to Groundwater Managers to Help Them Allocate Resources and Improve Their Programs.* Volume 1.

U.S. EPA (1998) The QTRACER Program for Tracer- Breakthrough Curve Analysis for Karst and Fractured-rock Aquifers. EPA/600/R-98/156a; EPA/600/R-98/156b.

> The QTRACER program was developed to provide a fast and easy method for evaluating tracer-breakthrough curves generated from tracing studies conducted in karst and fractured-rock aquifers. The results may then be applied in solute-transport modeling and risk assessment studies. The QTRACER document will serve as a technical guide to various groups who must address potential and/or exisiting ground-water contamination problems in karst and fractured-rock terrains. Tracing studies are always appropriate and probably necessary, but analysis can be difficult and tedious. This document and upcoming computer programs alleviate some of these problems.

U.S. EPA (1997) Appendix D: Conjunctive Delineation of the Zone of Ground Water Contribution and the Area of Surface Water Contribution to Public Water Systems. State Source Water Assessment and Protection Programs Guidance: Final Guidance; EPA 816-R-97-009; PA-9-A-11.

U.S. EPA (1997) State Methods for Delineating Source Water Protection Areas for Surface Water Supplied Sources for Drinking Water. EPA 816-R-97-008. 40 p.

> A review of federal, state, and local government methods to delineate surface source water protection areas (SWPA) in watersheds, or basins indicates that primarily three methods have been used. These methods are: (1) topographic boundary delineation; (2) setback/buffer zone delineation; and (3) time-of-travel calculation. Modeling techniques have been used to enhance these methods. A summary of these methods is presented. Examples are included. A comprehensive bibliography is included.

U.S. EPA, Office of Water. (1992) Case Studies in Wellhead Protection: Ten Examples of Innovative Wellhead Protection Programs. (EPA 813-R-92-002).

U.S. EPA, Office of Water (1991) Delineation of Wellhead Protection Areas in Fractured Rocks. 144 p.

U.S. EPA, Office of Water. (1989) Wellhead Protection Programs: Tools for Local Governments. (EPA 440/6-89-002).

Van Leeusenm M., C.B.M. Te Stroet, A.P. Butler, and J.A. Tompkins. (1999) Stochastic Determination of the Wierden (Netherlands) Capture Zones. Ground Water 37(1): 8-17.

> A spatial stochastic approach has been adopted to estimate the capture zones of a wellfield near the town of Wierden. The main sources of uncertainty were found to be the hydraulic conductivity of the productions aquifer and the spatial distribution and thickness of an impeding clay layer situated above the production aquifer.

Varljen, M.D., and J.M. Shafer. (1992) A Coupled Simulation-Optimization Technique for Protection Municipal Ground Water Supplies from Contamination. Proceedings of the Solving Ground Water Problems with Models Conference (February 11-13, 1992, Dallas, Texas [Ground Water Management Book 9]): 381-394.

A technique based upon numerical ground water flow modeling and unconstrained nonlinear optimization has been developed for the purpose of protecting municipal ground water supplies from contamination through capture zone management. The technique involves conventional finite-difference ground water flow modeling and numerical flowpath/travel time calculation coupled with nonlinear mathematical programming to specify pumping rates for wells in a wellfield such that the configuration of capture zones in relation to existing threatening land uses minimizes the risk of contamination while maintaining total water output from the wellfield. A principal feature of this technique is its ability to incorporate spatially varying aquifer properties. This approach to ground water quality management has several advantages over conventional wellhead protection (WHPA) delineation in that a greater level of protection can be achieved if threatening land uses are not even included in capture zones, rather than attempting to reduce the threat of existing land uses. Furthermore, the economic impacts of land use prohibitions and risk reductions instituted with WHPAs based on capture zones are correspondingly minimized if fewer threatening land uses are included in the capture zones.

Vassolo, S., W. Kinzelbach, and W. Schafer. (1998) Determination of a Well Head Protection Zone by Stochastic Inverse Modeling. Journal of Hydrology 206(3-4): 268-280.

Capture zones of wells play an important role in the protection of groundwater against pollution by persistent chemical compounds. As, however, the accuracy and uniqueness of groundwater flow models may be poor, the outcome of a deterministic modeling exercise is likely to be unreliable. In such a case, stochastic modeling presents an alternative for the delineation of capture zones. In this paper, two methods are compared: the unconditional and conditional Monte-Carlo simulation. In each method, realizations of the aquifer characterized by a combination of recharge rates and transmissivity values are produced. For each realization, the capture zone of the well is determined by particle tracking. By superposition of all capture zones produced, a probability distribution is obtained that describes the probability of a point on the ground surface to belong to the capture zone.

Vernon, J.H., Donohue, J.J., and D.S. Albaugh. (2002) Delineating Recharge Areas for Bedrock Wells: Case Study Examples. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 52-55.

This paper [resents case studies of recharge area delineations for wells constructed in fractured bedrock, in order to establish Source Protection Areas and/or to assess impacts that may occur as a result of pumping the wells.

Vernon, J.H., F.L. Paillet, W.H. Pedler, and W.J. Griswold. (1993) Application of Borehole Geophysics in Defining the Wellhead Protection Area for a Fractured Crystalline Bedrock Aquifer 34(1): 41-57.

Virginia Ground Water Protection Steering Committee. (No Date) Wellhead Protection: A Handbook for Local Governments in Virginia.

Virginia Ground Water Protection Steering Committee. (1993) Wellhead Protection: Case Studies of Six Local Governments in Virginia.

Waters, B., and J. Woaneiwicz. (2002) Integrated Approach to Development of High-Yield, Sustainable Groundwater Supplies from Fractured-Rock Aquifers. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 125.

This paper combines traditional geologic mapping and remote sensing analysis techniques with state-of-the-art geophysical technologies to locate targets for drilling, sophisticated derivative analysis of aquifer test data to develop and refine the conceptual flow model, and GIS-based land-use mapping techniques for delineating and managing aquifer protection areas.

Webbers, A. (1995) Ground-Water Quality Protection: Why It's Important To You. U.S. Geological Survey Open-File Report 95-376. Retrieved from the World Wide Web January 14, 2002 at: http://water.usgs.gov/pubs/of/ofr95376/

This brochure acquaints the reader with some of the common characteristics of ground water in carbonate (limestone and dolomite) rocks in Tennessee. It also emphasizes the importance of protecting the quality of these water supplies for present and future use.

WERF. (1999) Assessment of Availability and Use of Hydrodynamic, Runoff and Fate and Transport Models. WERF Project No. 99-WSM-5. Retrieved October 29, 2001 from the World Wide Web: www.werf.org/research/search/

A review and assessment of currently available models. Develops selection criteria and a process to determine the most appropriate model(s) for a particular situation or need.

Wilson, J.L., and W.R. Linderfelt. (1991) Groundwater Quality in Pumping Wells Located Near Surface Water Bodies. Technical Completion Report No. 261. New Mexico Water Resources Research Inst.

For wells located near surface water bodies, a variety of two-and three-dimensional analytical and numerical models of induced infiltration and capture zones are presented. The capture zone models use particle tracking. Two types of capture zones are defined: ultimate capture zones that include that portion of the aquifer that will eventually discharge to the well; and time-dependent capture zones that include only a portion of the aquifer that discharges to the well withing a prescribed time. Capture zone models involved uncertain parameters that lead to "fuzzy" capture zone boundaries.

Wilson, J. M., G. Achmad, and Anne Arundel County (Md.) Department of Public Works. (1995) Delineation of Wellhead Protection Areas Using Particle Tracking Analysis and Hydrogeologic Mapping, Northern Anne Arundel County, Maryland. 121 p.

Wilson, J.T., Mandell, W.A., Pailler, F.L., Bayless, E.R., Hanson, R.T., Kearl, P.M., Derfoot, W.B., Newhouse, M., and W.H. Pedler. (2002) An Evaluation of Borehole Flowmeters Used to Measure Horizontal Ground-Water Flow in Limestones of Indiana, Kentucky, and Tennessee, 1999. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 43.

Wireman, M. (2002) Characterization and Management of Ground-Water Resources in Fractured-Rock Hydrogeologic Settings. In: Fractured-Rock Aquifers 2002, March 13-15, 2002 Denver, Colorado. Pg. 1-5.

Wuolo, R.W., D.J. Dahlstrom, M.D. Fairbrother. (1995) Wellhead Protection Area Delineation Using the Analytic Element Method of Ground-water Modeling. Ground Water 33(1): 71-83.

Two analytic element models (SLAEM and MLAEM) were used to delineate wellhead protection areas for existing and proposed wells in Brooklyn Park by simulating steady state flow in outwash and bedrock aquifers. The analytic element method is compared with numerical modeling. A geologic cross section illustrating directions of ground water flow and table of stratigraphy are provided.

Zlotnik, V.A. (1997) Effects of Anisotropy on the Capture Zone of a Partially Penetrating Well. Ground Water 35(5): 842-847.

Dimensional analysis was used to study the effects of aquifer anisotropy on capture zone geometry for a partially penetrating well that is screened from the top of a confined aquifer. Dimensionless similarity criteria were identified which allow an extension of results for advective transport modeling from isotropic conditions to anisotropic ones. Anisotropy is useful in determining the size and shape of the capture zone under two conditions: (1) the pumping rates is small comparted to the scaled regional flow velocity; and (2) the well has a low degree of penetration.

Ongoing Research

Bedrock Regional Aquifer Systematics Study (BRASS) Project. Retrieved from the World Wide Web: http://geology.er.usgs.gov/eespteam/brass/brass.html

The BRASS project is developing cooperative research efforts to better understand groundwater flow, availability, and quality in regions underlain by fractured bedrock. Current projects are underway in Connecticut, New Hampshire, South Dakota, Pennsylvania and Maryland.

Loper, D. (2001) Steps Toward Better Models of Transport in Karstic Aquifers. *In:* U.S. Geological Survey Karst Interest Group Proceedings, Eve Kuniansky (Editor). U.S. Geological Survey Water-Resources Investigations Report 01-4011. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/ogw/karst/kigconference/dl_stepstoward.htm

An overview of the efforts of the Hydrogeology Consortium, a new scientific organization, to help develop and use better models of flow and transport in karstic aquifers.

Ondorff, R.C., J.B. Epstein, and D.J. Weary. (2001) Proposed National Atlas Karst Map. *In:* U.S. Geological Survey Karst Interest Group Proceedings, Eve Kuniansky (Editor). U.S. Geological Survey Water-Resources Investigations Report 01-4011. Retrieved October 26, 2001 from the World Wide Web:
http://water.usgs.gov/ogw/karst/kigconference/rco_proposedmap.htm

This report describes the features of the National Karst Map being prepared by the USGS and the National Park Service.

USGS. Effects of Ground-water Withdrawals on Ground-water Flow in the Sauk River Valley Aquifer and Streamflow in the Sauk River in the Cold Spring Area, Stearns County, Minnesota. USGS Project 156. Retrieved October 31, 2001 from the World Wide Web:
http://mn.water.usgs.gov/active_projects/156t.html

The Minnesota Department of Health and public and private water suppliers are concerned about effects of ground-water withdrawals from high-capacity wells on water levels in the aquifers, streamflow in the Sauk River, and potential sources of contamination to water-supply wells. Study seeks to delineate source-water area, 10- 20- and 30- year travel time, and determine changes in streamflow as related to appropriated ground-water withdrawals under current and anticipated development conditions.

USGS. Source-Water Assessment and Protection in Michigan Karst Terrain. D. Holtschlag, Principal Investigator. USGS Project MI089: Duration: 10/98 - 09/03. Retrieved October 25, 2001 from the World Wide Web: http://water.usgs.gov/owq/dwi/dist_projects/mi_karst.htm

> The objective of the project is to provide technical assistance to the state of Michigan's SWAP by developing approaches for and conducting SWAs for supplies obtained from ground water in karst terrain and from inland rivers, the Great Lakes, and the lower connecting channels.

USGS. Use of Low-Cost Data to Simulate Fractured-Aquifer Watersheds for Management of Water Quality and Quantity. Water Resources Research Grant Proposal. Eileen Poeter, Principal Investigator. Duration: 09/01 - 09/03. Retrieved November 1, 2001 from the World Wide Web: http://water.usgs.gov/wrri/01grants/national/CO261.html

> This study will use a database to integrate data from USGS and many other sources in order to better understand the system, and to determine which types of data are useful in describing the system and reduce uncertainty.

USGS, National Research Program. Analytical Modeling of Flow and Transport in Aquifers and Geothermal Reservoirs. Retrieved October 24, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/moench.html

> This project's objective is to obtain analytical solutions to specific problems of flow and transport in water- bearing formations that can be used for evaluating the hydraulic and transport properties of aquifers and geothermal reservoirs.

USGS, National Research Program. Hydrology of Fractured Rocks. Hsieh and Tiedeman, Principal Investigators. Retrieved October 25, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/hsieh.html

> The objectives of this study are to: (1) develop theoretical model of fluid flow and solute transport in fractured rocks; (2) develop field methods (hydraulic and tracer tests) to characterize the flow and transport properties of fractured rocks; and (3) combine the use of geological, geophysical, and geochemical methods with hydraulic and tracer tests to develop an integrated approach to modeling flow and transport in fractured rocks.

USGS, National Research Program. Mathematical Simulation of Subsurface-Water Flow Using Uncertain and Incomplete Data. Cooley and Hill, Principal Investigators. Retrieved October 25, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/cooley.html

> Project objectives are to: (1) reformulate where necessary, the equations describing the flow of fluids through porous or fractured rock to include stochastic processes, emphasizing equations that are suitable for field use; (2) derive methods to solve for

dependent variables and estimate parameters in the equations; (3) derive methods to assess the uncertainty of both the results computed using the model formed by the basic equations and the parameters estimated for the model; and (4) derive methods to assess the predictive capability of the model.

USGS, National Research Program. Transport Phenomena in Fractured Rock. Shapiro, Principal Investigator. Accessed October 25,2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/shapiro.html

This study focuses on the development of mathematical models of transport phenomena in fractured rock, and an investigation of the parameters which arise. In addition, physical situations where each conceptualization is applicable, and the adaptability of field measurements to these conceptualizations will be evaluated.

USGS, WRD. Delineation of Contributing Areas to Public Supply Wells in Aquifers with Complex Hydrogeologic Conditions. Forest Lyford, Project Chief. WRD Project # MA153. Retrieved October 22, 2001 from the World Wide Web: http://ma.water.usgs.gov/projects/MA153.htm

The primary objective of this investigation is to delineate the contributing areas for a select group of public-supply wells in Massachusetts located in complex hydrogeologic settings, including those in confined and fractured-rock aquifers. A secondary objective is to evaluate the effects of pumping in these settings on wetlands and surface water.

Williams Environmental Associates. Demonstrating Benefits of Wellhead Protection Programs. AWWARF Project No. 2778. To be completed in 2003.

This project will identify and develop a generic methodology to measure and quantify the benefits of Wellhead Protection Programs (WHPPs). Will also address the full range of benefits of WHPPs, including water quality benefits as well as economic and ecological benefits.

Surface Water Delineation

Recent Research

Alexander, R.B., R.A. Smith, M.J. Focazio, and M.A. Horn. (1999) Source-area Characteristics of Large Public Surface-water Supplies in the Conterminous United States: An Information Resource for Source-water Assessment. U.S. Geological Survey Open-File Report 99-248 Contact: Bill Ferguson, 303-236-8747 ext. 321

This CD-ROM includes information on water time of travel during average stream-flow conditions that could be used for segmenting the source-area watersheds. The source-area

data and calculations were originally assembled for the recently developed USGS national water-quality model SPARROW, and are summarized by source area in the CD-ROM data base.

Ball, J.E., M.J. White, G.de R. Innes, and L. Chen. (1993) Application of HSPF on the Upper Nepean Catchment. Hydrology and Water Resources Symposium, June 30-July 2, 1993. Newcastle, New South Wales, Australia, pp. 343-348.

Chew, C.Y., L.W. Moore, and R.H. Smith. (1991) Hydrological Simulation of Tennessee's North Reelfoot Creek. Watershed Res. J. WPCF 63(1):10-16.

Donigian, A.S., R.V. Chinnaswamy, A.S. Patwardhan, and R.M. Jacobson. (1996) Watershed Modeling of Pollutant Contributions and Water Quality in the LeSueur Basin of Southern Minnesota. *In*: Proceedings Watershed '96. Baltimore, Maryland, June 8-12, 1996. Retrieved October 26, 2001 from the World Wide Web: http://www.epa.gov/owow/watershed/Proceed/donigian.html

As part of the Minnesota River Project, the LeSueur Watershed is being modeled with the U.S. EPA Hydrologic Simulation Program - FORTRAN (HSPF) to identify and quantify the relative pollutant contributions from both point and nonpoint sources, and to help evaluate the effects of alternative agricultural BMPs on water quality and pollutant loadings to the main stem of the Minnesota River. This paper briefly describes the model application procedures, watershed representation and preliminary calibration results, along with indications of future modeling directions.

Garbrecht, J., F. Ogden, P.A. DeBarry, and D.R. Maidment. (2001) GIS and Distributed Watershed Models. I: Data Coverages and Sources. J. Hydrol. Eng. 6(6):506-514.

This two-part paper provides an integrated overview of the multiple facets of data-GIS-modeling issues and a source of background information for selection and application of GIS in watershed modeling.

Holtschlag, D.J. and S.S. Aichele. (2001) Visualization of Drifting Buoy Deployments on St. Clair River near Public Water Intakes–October 3-5, 2000. U.S. Geological Survey Open File Report 01-17. Retrieved October 26, 2001 from the World Wide Web: http://smig.usgs.gov/features_0301/drifters.html

Drifting buoys were deployed to help investigate flow characteristics near public water intakes in ten reaches of St. Clair River from October 3-5, 2000. Turbulent dispersion characteristics and flow patterns of the river were determined by buoys equipped with GPS receivers.

Scheckenberger, R.B. and A.S. Kennedy. (1994) The Use of HSP-F in Subwatershed Planning. *In*: Current Practices in Modelling the Management of Stormwater Impacts, W. James (Editor). Lewis Publishers, Boca Raton, Florida, pp. 175-187.

Schnabel, R.R. and R.L. Day. (1998) Development Of GIS To Delineate Watersheds In Pennsylvania Where Riparian Processes Improve Water Quality. Agronomy & Soil Science, Pennsylvania State University, University Park, Pennsylvania. (USDA Cooperative Agreement).

> Develop a GIS for locating watersheds with geomorphic factors favoring N removal from groundwater. Test hypothesis that watersheds with geomorphic features favoring riparian zone control will have greater differences between stream baseflow and groundwater nitrate concentration.

Whipple, Jr., William. (1993) Buffer Zones Around Water-Supply Reservoirs. Journal of Water Resources Planning and Management 119:495-499.

> This report includes discussions of relationships between runoff time of travel and setback characteristics.

Ongoing Research

Gutierrez-Magness, A. Development of a Calibrated Watershed Model, Potomac River Basin. WRD Project # MD163. Project duration: 7/01 - 6/04. Retrieved October 25, 2001 from the World Wide Web: http://md.water.usgs.gov/projects/md163.htm

> Objectives for the study are to: (1) compile necessary databases for simulation of Potomac watershed processes using HSPF, (2) create watershed segmentation, river reach segmentation, and associated control files from HSPF simulation of River basin, (3) develop and implement innovative calibration procedures, such as inverse modeling and analysis of scaled model sensitivities, to improve HSPF model calibration, (4) calibrate the HSPF model, and (5) produce reports on calibration of watershed model, analysis of calibration strategies, model uncertainty, analysis of results, and implications for future monitoring and data collection activities.

Viger, R.J., S.L. Markstrom, and G.H. Leavesley. The GIS Weasel - An Interface for the Treatment of Spatial Information Used in Watershed Modeling and Water Resource Management. *In*: Proceedings of the First Federal Interagency Hydrologic Modeling Conference, April 19-23, 1998, Las Vegas, Nevada. 2(7):73-80. Retrieved November 5, 2001 from the World Wide Web: http://wwwbrr.cu.usgs.gov/weasel./doc/ffiamc/

> The GIS Weasel is being developed to aid hydrologists and other physical modelers in the delineation, characterization, and parameterization of an area of interests, drainage nets,

and modeling response units. The only data requirement is a digital elevation model describing the area of interest.

Water Resources of New Hampshire and Vermont. Time of Travel Assessments for Source Water Protection. Retrieved November 2, 2001 from the World Wide Web: http://nh.water.usgs.gov/CurrentProjects/tot/tot.htm

The State's Department of Environmental Services and the USGS is conducting time-of-travel assessments for 13 river reaches in New Hampshire/Vermont. Results from these assessments will be utilized for mapping 6-hour contaminant travel boundaries.

Source Inventory Methodologies

Recent Research

Bowman, A.M., A.K. Graves, K. Hix, and C. Hagedorn. (2001) Determining Sources of Fecal Pollution in the Blackwater River Watershed. Presented at the 101st Annual American Society for Microbiology Meeting, May 20-24, 2001, Orlando, Florida. Retrieved December 20, 2001 from the World Wide Web: http://www.bsi.vt.edu/biol_4684/BST/BSTprojects.htm

Antibiotic resistance analysis (ARA) was used to determine sources of fecal pollution in the Blackwater River in south central Virginia. The Virginia Department of Environmental Quality designated seven segments as impaired due to fecal coliforms with non-point source (NPS) agriculture the suspected source of impairment. The Blackwater River watershed encompasses over 72,000 ha of dairy, beef, and intensive production agriculture, abundant wildlife populations in forested areas, and hundreds of homes with onsite septic systems. A library of antibiotic resistance profiles based on 30 drug/concentration combinations was developed for 1,451 enterococcus isolates from human, cattle, chicken, horse, goat, sheep, deer, raccoon, muskrat, goose, duck, coyote, and wild turkey. Each isolate was classified as human, wildlife or livestock. Correct classification rates were 82.3% for human, 86.2% for livestock and 87.4% for wildlife isolates. Profiles were then determined for 48 isolates from each stream sample, collected periodically from September 1999 to August 2000, and compared to the known sources using discriminant analysis. A human signature was found at each of 9 sites at least once during the sampling period, ranging from 2.1 to 56.2% of the profiled isolates. The livestock signature varied from 12.5% to 91.7% over sites and months, and the wildlife signature varied from 4.2% to 70.8%. The results indicate that both humans and wildlife contribute to fecal pollution in addition to the suspected source, livestock, and reducing fecal pollution in the Blackwater River watershed will require consideration of all three sources.

Ebbert, J.C., S.S. Embrey, R.W. Black, A.J. Tesoriero, and A.L. Haggland. (2000) Water Quality in the Puget Sound Basin, Washington and British Columbia, 1996-98. USGS Circular 1216. Retrieved November 8, 2001 from the World Wide Web: http://water.usgs.gov/pubs/circ/circ1216/

> This study in the Puget Sound Basin analyzes historically used pesticides in relation to detection in streams and rivers. Compared pesticides detected in urban streams with retail sales, which suggested that homeowner and nonresidential applications both are sources of pesticides in streams. By analyzing contaminants in streams and rivers, sources of contamination can be identified by correlating the historical and known land usage.

Graves, A.K., A.M. Bowman, M. Mahal, and C. Hagedorn. (2001) Determining Sources of Fecal Pollution for a Rural Unsewered Community. Presented at the 101st Annual American Society for Microbiology Meeting, May 20-24, 2001, Orlando, Florida. Retrieved December 20, 2001 from the World Wide Web: http://www.bsi.vt.edu/biol_4684/BST/BSTprojects.htm

> Bacterial Source Tracking (BST) methodology was used to determine sources of fecal pollution in Millwood, VA. Millwood consists of 71 homes, all served by individual septic systems of indeterminate age and performance, and a stream (Spout Run) passes through the center of the community. Stream and well samples were collected monthly and analyzed for fecal coliforms and enterococci. Twelve percent of the well samples and 92% of the stream samples were positive for fecal coliforms, and 26% of the stream samples exceeded the recreational water standard (1000 fecal coliforms/100ml). Antibiotic Resistance Analysis (ARA) was preformed on enterococci recovered from Spout Run in upper, middle, and lower Millwood. Isolates of human origin appeared in upper, middle, and lower Millwood and ranged from 2.0% to 42% of the sourced isolates over sampling sites and seasons. The percentage of human origin isolates was highest in upper and middle Millwood, and declined downstream from that point. These results were obtained by comparing the antibiotic resistance profiles of stream isolates against a library of 1,174 known source isolates with correct classification rates for the known sources of 94.6% for human isolates, 93.7% for livestock isolates, and 87.8% for wildlife isolates. The main impairment in water samples was fecal coliforms, as no other problems were identified based on water chemistry analyses for both well and stream water samples.

Hager, Mary Catherine. (2001) Detecting Bacteria in Coastal Waters 2. Stormwater 2(6). Retrieved December 20, 2001 from the World Wide Web: http://216.55.25.242/sw_0105_detecting.html

> BST methods appear to provide the best available means of determining origins of fecal contamination of water bodies. Projects involving TMDL development for fecal coliforms, and those designing and implementing BMPs to reduce fecal loading in water, would likely benefit from the use of BST methods. Part 1 of this two-part article includes

an overview of detection methods and describes ribotyping, toxin biomarker, and antibiotic resistance analysis techniques. Part 2 examines reverse transcriptase-polymerase chain reaction, pulse field gel electrophoresis, and F-specific coliphage typing.

Mining Sites: Database of Current and Historic Mining Sites (CD-ROM). Contact Bill Ferguson, 303-236-8747 ext. 321

New England Interstate Water Pollution Control Commission. (2000) SWAP Technical Assistance Document: The Application of GIS Technology and Data Management in States' Source Water Assessment Programs. October. Retrieved January 8, 2002 from the World Wide Web: http://www.neiwpcc.org/swap.pdf

This report addresses states' SWAP/ source protection related data quality, coordination, management, and distribution issues and concerns. This document highlights five states' approaches (Pennsylvania, Washington, Ohio, Iowa, and Nevada) to using GIS in their Source Water Assessment Programs.

Ohio River Valley Water Sanitation Commission (ORSANCO). Available on the World Wide Web: http://www.orsanco.org

ORSANCO coordinates information exchange between neighboring states so that the interstate aspects of source water protection activities can be addressed. To facilitate a data transfer between states on contamination sources, ORSANCO established minimum information requirements for point sources of contamination. Required information includes: facility name, address, and contact/telephone number, facility ID number, NPDES permit number, latitude/longitude, chemical(s) released, quantity information, and SIC code.

ORSANCO produced the document, *Resources for Interstate Source Water Protection Programs*, which describes interstate source water protection programs being implemented in the U.S. The report describes activities within 18 river basins. It is available on its website.

Pesticide National Synthesis Project. Available on the World Wide Web: http://ca.water.usgs.gov/pnsp/

National assessment of pesticides in the streams, rivers, and ground water of the United States. The program began in 1991 with the purpose of producing a long-term assessment of the status of and trends in the quality of the Nation's water resources.

Standridge, Jon. (No Date) Sources of *Cryptosporidium* in Watersheds. WERF Project No. 99-HHE-2. Retrieved October 29, 2001 from the World Wide Web: www.werf.org/research/search/

Identifies the sources and magnitude of *Cryptosporidium* by broad characterization of rural, suburban, and urban land uses. Associates the source(s) to urban stormwater and WWTP outflows and during baseflow and stormwater events.

U.S. Army Center for Health Promotion and Preventative Medicine. (1999) User's Guide for Source Water Assessment and Protection at U.S. Army Installations. Retrieved November 8, 2001 from the World Wide Web: http://water.usgs.gov/usaec/techguide.html

The purpose of this guidance document is to provide U.S. Army installations, that operate, own, or partially own a drinking water treatment system, with guidance on developing source water assessment and protection programs pursuant to the 1996 SDWA Amendments. Installations should have a number of data sources that will identify potential contamination threats. Spill Prevention Control and Countermeasure (SPCC) plans, lists of extremely hazardous substances, and hazardous waste management plans are developed for most installations, and should be examined.

U.S. EPA, Office of Water. (1991) Guide for Conducting Contaminant Source Inventories for Public Drinking Water Supplies: Technical Assistance Document. 570/9-91-014. December.

This Technical Assistance Document discusses the design, structure and function of contaminant source inventories. It describes how to conduct an inventory, and presents methods for identifying potential contamination sources, including existing data sources, survey, and field studies.

USGS. Land Use and Land Cover Data - Digital Maps: http://nsdi.usgs.gov/products/lulc.html

Land use and land cover (LULC) data are derived from thematic overlays registered to 1:250,000-scale base maps and a limited number of 1:100,000-scale base maps. Land use and land cover data provides information on urban or built up land, agricultural land, rangeland, forest land, water, wetlands, barren land, tundra, and perennial snow or ice. Associated maps display information in five data categories: (1) political units, (2) hydrologic units, (3) census county subdivisions, (4) Federal land ownership, and (5) State land ownership.

USGS. National Pesticide Use Maps: http://ca.water.usgs.gov/pnsp/use92/

Maps of annual pesticide use have been compiled for 208 compounds used in U.S. crop production. The maps are based on pesticide use rates compiled by the National Center for Food and Agricultural Policy (NCFAP) from pesticide use information collected by state and federal agencies over a four year period (1990 -1993 and 1995), and on crop acreage data obtained from the 1992 Census of Agriculture. The NCFAP database contains state-based estimates of pesticide use rates for 208 compounds and 87 crops.

USGS. National Water Quality Assessment Data Warehouse: http://infotrek.er.usgs.gov/pls/nawqa/nawqa.home

Chemical, biological, and physical water quality data from study units (basins) across the nation. This data warehouse contains data from the first 36 study units. Data from the 15 study units started in 1997 will be incorporated later.

USGS, National Water Quality Assessment Program. Summary Reports from Most of the First 20 Study Units. http://water.usgs.gov/public/pubs/nawqasum/index.html

Each publication in the series includes a summary of local water-quality issues and findings; several sections describing local findings in greater detail; and several sections putting local findings in a national context. Issues discussed include nutrients, pesticides, volatile organic compounds, radon, and suspended sediment in ground water and surface water; and semi-volatile organic compounds, organochlorine compounds, and trace elements in bed sediment and aquatic biota.

USGS. (1995) Magnetic Surveys for Locating Abandoned Wells. Fact Sheet 163-95, January. Retrieved November 5, 2001 from the World Wide Web: http://greenwood.cr.usgs.gov/pub/fact-sheets/fs-0163-95/FS163-95.html

Carefully designed ground magnetic or aeromagnetic surveys can be used to locate abandoned wells by mapping the magnetic disturbances produced by their steel well casings. The USGS can conduct, process, and interpret such surveys, or it can aid in the design and monitoring of contracts for such surveys.

USGS Toxic Substances Hydrology Program. (No Date) Research On Nonpoint Sources of Ground Water Contamination in Relation to Land Use. Bibliography. Retrieved November 5, 2001 from the World Wide Web: http://toxics.usgs.gov/bib/bib-nonpt-gw-cont-title.html

This is a bibliography of 66 papers from 1978 to the present on regional groundwater assessments, including assessment of nonpoint sources of contamination and examination of land uses.

USGS, Toxic Substances Hydrology Program: http://toxics.usgs.gov/

The Toxic Substances Hydrology Program provides objective scientific information to improve characterization and management of contaminated sites, to protect human and environmental health, and to reduce potential future contamination problems.

Water Quality Information Center, National Agricultural Library. Agricultural Research Service, USDA. Available on the World Wide Web: http://www.nal.usda.gov/wqic/

> Electronic access to information on water and agriculture. Contains links to several databases and bibliographies.

Watershed Information Resource System (WIRS) Database: http://www.terrene.org/wirsdata.htm

> The WIRS database currently indexes and abstracts some 5,000 watershed-related documents, both recent and classic studies. Documents published within the past five years comprise about 25 percent of the database. Includes information on point and nonpoint sources of pollution.

Ongoing Research

American Water Works Service Company, Clancy Environmental Consultants, Technology Planning and Management Corporation, and Hagler Bailly Services, Inc. Source Water Assessment: Variability of Pathogen Concentration. AWWARF Project No. 488. Research partner: M/DBP Council. To be completed in 2002.

> This project will determine watershed processes and characteristics that influence pathogen loading at water treatment plants. Will also estimate resulting extreme and average pathogen concentrations.

CRC for Water Quality and Treatment (Australia). Hydrodynamic Distribution of Pathogens in Lakes and Reservoirs. AWWARF Project No. 2752. Research partner: USEPA. To be completed in 2004.

> This project will develop, test, and verify techniques that will help utilities monitor and predict the dynamic and non-uniform distribution of pathogens in lakes and reservoirs.

Eddy-Miller, and G. Gerhard. (1999) Results of Nitrate Sampling in the Torrington, Wyoming, Wellhead Protection Area, 1994-1998. USGS Water-Resources Investigations Report 99-4164.

> A monitoring program for nitrate in ground water in and near Torrington, Wyoming was conducted by the Town of Torrington from April 1994 through March 1997, and cooperatively by the Town of Torrington and the U.S. Geological Survey from May 1997 through August 1998. Trends in nitrate concentrations were determined for the period of time covered by both monitoring programs. A significant trend was detected at 34 of the 72 sites. Twenty-six sites had nitrate concentrations that were increasing, and eight sites had nitrate concentrations that were decreasing. Nitrogen isotope data were also collected at selected sites. These data indicate that the source of nitrate in ground water in and

around Torrington is probably not from human or animal waste, but rather organic soil nitrogen, or ammonium or nitrate fertilizer.

Metropolitan Water District of Southern California (Los Angeles) and U.S. Geological Survey. National Assessment of MTBE Occurrence in Drinking Water. AWWARF Project No. 2507. To be completed in 2002.

This project will develop a representational national database of MTBE concentrations in both groundwater and surface water supplies.

National Reconnaissance of Emerging Contaminants in the Nation's Water Resources. Retrieved from the World Wide Web October 30, 2001: http://toxics.usgs.gov/regional/emc.html

The USGS, through the Toxic Substances Hydrology Program, has implemented a national reconnaissance to provide baseline information on the environmental occurrence of emerging contaminants in water resources. USGS researchers are developing and/or refining the analytical methods to measure a wide variety of emerging contaminants at trace levels (<1 ppb). Currently, a total of 94 target chemicals are being measured in water samples including 22 human and veterinary antibiotics, 13 prescription drugs, 5 nonprescription drugs, 39 industrial and household wastewater products (e.g., caffeine, flame retardants, and personal care products), and 15 reproductive and steroidal hormones.

Stroud Water Research Center, et al. Evaluation of Sources of Pathogens and NOM in Watersheds. AWWARF Project No. 251. To be completed in 2001.

This project will determine the distribution and densities of Giardia and Cryptosporidium and the concentrations of NOM (natural organic matter) in watersheds, and evaluate potential sources in field studies. It will develop potential source control strategies that will mitigate the concentrations of these contaminants in influent water resulting in potential treatment savings.

Technology Planning and Management Corporation. Chemical Occurrence Data Sets for Source Water Assessments. AWWARF Project No. 2756. To be completed in 2003.

This project will identify, list, and characterize chemical occurrence data sets that can be used in source water assessments. Will also produce a directory of all relevant source water assessment data to serve as a resource for agencies in improving source water assessment regulations and programs.

University of California at Berkeley. Occurrence Survey of Pharmaceutically Active Compounds. AWWARF Project No. 2617. Research partner: WRF. To be completed in 2004.

This project will investigate the occurrence of a limited number of pharmaceutically active compounds in source and treated waters. Will also use findings to further define and prioritize future research on the occurrence, treatment, and potential public health impacts of pharmaceutically active compounds in water.

Upstate Freshwater Institute (Syracuse, N.Y.) and Michigan Technological University. Model for Trihalomethane Precursors in Lakes and Rivers. AWWARF Project No 557. To be completed in 2002.

This project will quantify the relative contributions of external and internal sources to the THM precursor pools of five water supply reservoirs. Will identify, characterize, and quantify the sources and sinks of precursors in reservoirs. Will also develop and test a mechanistic model capable of simulating the magnitude and dynamics of the precursor pool in a single productive water supply reservoir.

USGS Initiative Implementation Team and Colorado and Montana Watershed Teams. 1997-2001. USGS Abandoned Mine Lands Initiative. Retrieved November 5, 2001 from the World Wide Web: http://rockyweb.cr.usgs.gov/html/aml/workplan.html

Numerous abandoned or inactive mining sites are located on or adjacent to public lands administered by the Federal Land Management Agencies (FLMA). USGS plans to implement an Abandoned Mine Lands Initiative during fiscal years 1997 through 2001 to provide technical assistance in support of remediation of abandoned mine lands (AML) by FLMA. The Initiative will be implemented on a pilot scale in two watersheds, one each in Montana and Colorado. Because a complete inventory does not exist and would take years to assemble, the activities of the FLMA have focused on a watershed, rather than a site by site, approach to identify those priority watersheds within a state that are most at risk for environmental degradation from AML.

USGS. Water Resources Research Grant Proposal. "Source Water Protection Assessment Tools Development." March 1, 2001 to February 28, 2002. Retrieved November 2, 2001 from the World Wide Web: http://water.usgs.gov/wrri/01grants/UT3401.pdf

The susceptibility of source waters to contamination is to be determined for public water systems. Included in the specific research tasks is the development of a pollution source inventory database that will interface with the exposure assessment system to provide information that may be used in the transport models and in risk characterization.

Vulnerability and Sensitivity Assessments

Recent Research

Adams, B. and A.M. MacDonald. (1998) Aquifer Susceptibility to Side-effects of Groundwater

Exploitation. *In*: Groundwater Pollution, Aquifer Recharge and Vulnerability, N.S. Robins (Editor). Geological Society, London, Special Publications, 130, pp. 71-76.

Agency for Toxic Substances and Disease Registry (ATSDR). (1993) Toxicological Profile for Aldrin/Dieldrin (Update). Agency for Toxic Substances and Disease Registry, Atlanta, Georgia, 184 pp.

Aller, L., T. Bennett, J.H. Lehr, R.J. Petty, and G. Hackett. (1987) DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings. EPA Report 600-2-87/035. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. EPA, Ada, Oklahoma, 455 pp.

ATSDR. (1997) Toxicological Profile for Manganese (Update). Draft for public comment. U.S. Department of Health and Human Services, Public Health Service, 201 pp.

Atherholt, T.B., M.W. LeChevallier, W.D. Norton, and J.S. Rosen. (1998) Effect of Rainfall on Giardia and Crypto. Journal of the American Water Works Association 90(9):66-80. Executive summary available on the World Wide Web: http://www.awwa.org/journal/j998es1.htm

Baker, D.B. and R.P. Richards. (2000) Effects of Watershed Scale on Agrochemical Concentration Patterns in Midwestern Streams. *In*: Agrochemical Fate and Movement: Perspective and Scale of Study, T.R. Steinheimer, L.J. Ross, and T.D. Spittler (Editors). American Chemical Society, Washington, DC, pp. 46-64.

Barbash, J.E. and E.A. Resek. (1996) Pesticides in Ground Water: Distribution, Trends, and Governing Factors. Ann Arbor Press, Inc., Chelsea, Michigan.

Bekesia, G. and J. McConchieb. (2000) Empirical Assessment of the Influence of Unsaturated Zone on Aquifer Vulnerability, Manawatu, New Zealand. Ground Water 38(2):193-199.

Burkart, M.R. and D.W. Kolpin. (1993) Hydrologic and Land-use Factors Associated with Herbicides and Nitrate in Near-surface Aquifers. Journal of Environmental Quality 22(4):646-656.

Burkart, M.R., D.W. Kolpin, R.J. Jaquis, and K.J. Cole. (1999) Agrichemicals in Ground Water of the Midwestern USA: Relations to Soil Characteristics. Journal of Environmental Quality 28(6):908-1915.

Connecticut Department of Public Health and Connecticut Department of Environmental Protection (CDPH and CDEP). (1999) State of Connecticut Source Water Assessment Program: Work Plan. Retrieved January 22, 2002 from the World Wide Web: http://www.dph.state.ct.us/BRS/WSS/swap.htm

Correll, D.L., T.E. Jordan, and D.E. Weller. (1999) Precipitation Effects on Sediment and Associated Nutrient Discharges from Rhode River Watersheds. Journal of Environmental Quality 28(6):1897-1907.

Craun, G.F. and R.L. Calderon. (2001) Waterborne Disease Outbreaks Caused by Distribution System Deficiencies. Journal of the American Water Works Association 93:64-75.

Daly, M.H. and B.D. Lindsey. (1996) Occurrence and Concentrations of Volatile Organic Compounds in Shallow Ground Water in the Lower Susquehanna River Basin, Pennsylvania and Maryland. U.S. Geological Survey Water Resources Investigations Report 96-4141. Retrieved January 22, 2002 from the World Wide Web: http://wwwpah2o.er.usgs.gov/reports/wrir_96-4141/report.html#HDR0

DeSimone, L.A. and L.J. Ostiguy. (1999) A Vulnerability Assessment of Public-Supply Wells in Rhode Island. U.S. Geological Survey Water Resources Investigations Report 99-4160. U.S. Geological Survey, Northborough, Massachusetts, 153 pp.

Domenico, P.A. and F.W. Schwartz. (1998) Physical and Chemical Hydrogeology. Second edition. John Wiley & Sons, Inc, New York, New York.

Druliner, A.D. and T.S. McGrath. (1996) Predicting Nitrate-Nitrogen and Atrazine Contamination in the High Plains Aquifer in Nebraska. U.S. Geological Survey Water-Resources Investigations Report 95-4202. U.S. Geological Survey, Lincoln, Nebraska. Retrieved January 22, 2002 from the World Wide Web: http://www-ne.cr.usgs.gov/reports/nitrate.html

Duncan, D., D.T. Pederson, T.R. Shepherd, and J.D. Carr. (1991) Atrazine Used as a Tracer of Induced Recharge. Ground Water Monitoring Review 11(4):144-150.

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Focazio, M.J., R.A. Smith, R.B. Alexander, and G.E. Schwarz. (1997) A National Model for Assessing the Susceptibility of Surface-water Supplies to Source-area Contamination. *In*: Proceedings, Source Water Protection 98, Dallas, Texas, April 1998.

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Gollnitz, W.D. (1999) Induced Infiltration Rate Variability and Water Quality Sampling Issues. Proceedings of the International Riverbank Filtration Conference. November 4-6, 1999. Louisville, Kentucky.

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Hallberg, G.R. (1989a) Pesticide Pollution of Groundwater in the Humid United States. Agriculture, Ecosystems and Environment 26:299-367.

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Hallberg, G.R. (1996) Water Quality and Watersheds: an Iowa Perspective. *In*: Proceedings Agriculture and Environment- Building Local Partnerships. pp. 1-5 to 1-22.

Hallberg, G.R. and D.R. Keeney. (1993) Nitrate. *In*: Regional Ground Water Quality, W.M. Alley (Editor). Van Nostrand Reinhold, New York, New York, pp. 297-321.

Hallberg, G.R., D.G. Riley, J.R. Kantamneni, P.J. Weyer, and R.D. Kelley. (1996) Assessment of Iowa Safe Drinking Water Act Monitoring Data: 1988-1995. Research Report No. 97-1. The University of Iowa Hygienic Laboratory, Iowa City, Iowa, 132 pp.

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Hochstedler, M.E., D. Larabee-Zierath, and G.R. Hallberg. (2000) Pesticides in Ambient Air and Precipitation in Rural, Urban, and Isolated Areas in Eastern Iowa. *In*: Agrochemical Fate and Movement: Perspective and Scale of Study, T.R. Steinheimer, L.J. Ross, and T.D. Spittler (Editors). American Chemical Society, Washington, DC, pp. 217-231.

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Kolpin, D.W. and S.J. Kalkhoff. (1993) Atrazine Degradation in a Small Stream in Iowa. Environmental Science and Technology 27(1):134-139.

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Ongoing Research

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CRC for Water Quality and Treatment (Australia). (Ongoing) Hydrodynamic Distribution of Pathogens in Lakes and Reservoirs. AWWARF Project No. 2752. Research partner: U.S. EPA. To be completed in 2004.

Lawrence Livermore National Laboratory. (Ongoing) Isotopic Tracers of Nonpoint-Source Pollution in Surface Water. AWWARF Project No. 376. To be completed in 2002.

Metropolitan Water District of Southern California (Los Angeles) and Montgomery Watson. National Assessment of Perchlorate Contamination Occurrence. AWWARF Project No. 2508. To be completed in 2002.

> This project will identify areas across the United States at high potential for environmental perchlorate contamination, and rank the likelihood of the presence of perchlorate contamination in a water utility source water. Will also conduct targeted sampling at those utilities most likely to be impacted by perchlorate contamination.

University of Iowa, Metropolitan Water District of Southern California (Los Angeles), and Orange County (Calif.) Water District. (Ongoing) Factors Affecting the Formation of N-Nitrosodimethylamine (NDMA) in Water and Occurrence. AWWARF Project No. 2678. Research partner: WERF. To be completed in 2004.

University of Massachusetts at Amherst. (Ongoing) Development of Event-Based Pathogen Monitoring Strategies for Watersheds. AWWARF Project No. 2671. Research partner: U.S. EPA. To be completed in 2003.

University of Ottawa and American Water Works Service Company. (1999) *Giardia* Cyst and *Cryptosporidiu*m Oocyst Survival in Watersheds and Factors Affecting Inactivation. AWWARF Project No.151.

> This project evaluates the survival of Cryptosporidium oocysts and Giardia cysts exposed to differing environmental conditions and determines subsequent effects on disinfection efficiency. Studies effects of temperature, age, and physical stress on viability and susceptibility to disinfection.

USGS. (Ongoing) OTIS - a Simulation Model Used to Characterize the Fate and Transport of Water-borne Solutes in Streams and Rivers. Retrieved October 26, 2001 from the World Wide Web: http://co.water.usgs.gov/otis/about/

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USGS. National Research Program Project. (Ongoing) Transport of Dissolved and Suspended Materials in Surface Waters. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/lee.html

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USGS, National Research Program Project. (Ongoing) Ground-Water Solute Transport Simulation. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/kipp.html

USGS, National Research Program Project. (Ongoing) Digital Monitoring of Transport in the Saturated Zone. Retrieved October 26, 2001 from the World Wide Web: http://water.usgs.gov/nrp/proj.bib/konikow.html

Wisconsin Geological and Natural History Survey. (Ongoing) Movement of Chemical and Microbial Contaminants Through Aquitards. AWWARF Project No. 2780. To be completed in 2003.

Preventive Measures Against Sources of Contamination

General Studies of BMPs

Recent Research

Dissmeyer, George E. (Editor). (2000) Drinking Water from Forests and Grasslands: A Synthesis of the Scientific Literature. USDA Forest Service, Southern Research Station. General Technical Report SRS-39. September. Retrieved October 22, 2001 from the World Wide Web: http://www.srs.fs.fed.us/pubs/gtr/gtr_srs039

> A review of scientific literature on the potential of common land-use practices to introduce contaminants into public drinking water sources. Briefly mentions research needs related to BMPS for the various contamination sources presented.

Koustas, Richard N. (2000) Urban Stormwater Best Management Practices. AWWF Research Focus Area. Draft. November.

> This research plan describes the Urban Watershed Management Branch (UWMB) approach to BMP research and to identify research needs and propose branch projects.

North Carolina State University. (No Date) Watersheds: A Decision Support System for Nonpoint Source Pollution Control. Retrieved January 17, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/index.html

Outen, D. (No Date) An Evaluation of the Functions and Effectiveness of Riparian Forest Buffers. WERF Project No. 99-WSM-4. Retrieved October 29, 2001 from the World Wide Web: www.werf.org/research/search/

> This project will quantify the hydrologic and water quality effects of buffer zones in urban and suburban areas, establish correlations with different types of buffers and resulting water quality, and begin to measure the impacts of various land uses on discharges.

Statewide Storm Water Quality Task Force. (No Date) Texas Nonpoint SourceBOOK. Retrieved January 17, 2002 from the World Wide Web: www.txnpsbook.org

> Contains four manuals on stormwater BMPs, including "Urban Nonpoint Source Management" and an interactive BMP selector.

U.S. EPA. (1996) Risk Management Research Plan for Wet Weather Flows. EPA 600/R-96/140, November. Retrieved January 17, 2002 from the World Wide Web: http://www.epa.gov/ednnrmrl/repository/wwfplan/wwfrp1.htm

U.S. EPA, Office of Science and Technology. (1999) Preliminary Data Summary of Urban Stormwater Best Management Practices. EPA-821-R-99-012, August. Retrieved January 17, 2002 from the World Wide Web: http://www.epa.gov/OST/stormwater/

Topics covered include: BMP performance measures and measurable goals, availability of measurement methods, design criteria, monitoring issues, costs and cost minimization opportunities, and the benefits and economic impacts of constructing and operating BMPs.

U.S. EPA, Office of Wetlands, Oceans, and Watersheds. (1993) Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. EPA-840-B-93-001c, January. Retrieved November 2, 2001 from the World Wide Web: http://www.epa.gov/owow/nps/MMGI/

This guidance specifies management measures for sources of nonpoint pollution. Tables compare the effectiveness of several practices in removing a variety of contaminants; costs are provided as well. The guidance summarizes other studies.

Wear, D.N., M.G. Turner, and R.J. Caiman. (1998) Land Cover along an Urban-Rural Gradient: Implications for Water Quality. Ecological Applications 8:619-630. Retrieved October 18, 2001 from the World Wide Web: http://www.rtp.srs.fs.fed.us/econ/pubs/dnw981.htm

Research identified patterns of change that may be most significant for water quality. Findings demonstrate how landscape simulation approaches can be used to identify where and how land use decisions may have a critical influence over environmental quality, thereby focusing both future research and monitoring effects and watershed protection measures.

Ongoing Research

Black and Veatch. Post-Project Monitoring of BMPs/SUDS to Determine Performance and Whole-Life Costs. AWWARF Project. To be completed in 2005.

This project is jointly funded by WERF, UKWIR and AwwaRF. It will develop guidance on the performance of different BMPs /SUDs, maintenance needs and whole life costs.

Louisville (Ky.) Water Company. Bank Filtration as a Treatment Process for DBP Precursor and Microbial Contaminant Removal. AWWARF Project No. 2622. Research partner: Louisville Water Company. To be completed in 2002.

This project will develop information on the removal of DBP precursors, herbicides and microbial contaminants as a function of bank filtration variables including raw water quality, filtration distance and velocity, temperature and riverbed sediments. Will also

study the mechanisms of DBP precursor removal in bank filtration process, and distinguish the contribution of physical, physical-chemical, and biological processes to the removal.

Water Process Inc. Impacts of Major Point and Non-Point Sources on Raw Water Treatability. AWWARF Project No. 2616. Research partner: WERF. To be completed in 2002.

This project will evaluate the impacts of point and non-point source discharges from publicly owned treatment works, combined sewer overflows, and agriculture (to include but not be limited to concentrated animal feeding operations) on drinking water source water quality, drinking water treatability, and water treatment costs. Will also evaluate the potential for using best available technologies and best management practices to mitigate impacts prior to the water treatment plant intake.

Storm Water BMPs

Recent Research

Bartone, Denise M. and Christopher G. Uchrin. (1999) Comparison of Pollutant Removal Efficiency for Two Residential Storm Water Basins. Journal of Environmental Engineering 125(7):674-677.

Detention basins with a low-flow concrete channel or a vegetated channel are two types of storm water collection basins examined in this study to assess effectiveness in water quality improvement. Influent and effluent data collected from four storm events include flow, petroleum hydrocarbons, nutrients, total suspended solids, three major ions, and indicator organisms. The calculation of influent and effluent mass loading for each basin determines the removal efficiency, which is used to rank the more effective basin for water quality improvement. As expected, the detention basin with a low-flow concrete channel was found to be ineffective for improving the water quality of storm water. The vegetated detention basin was also found essentially ineffective for water quality improvement for all four storms, with low influent mass loading and flushing of stored water the most probable reasons for this result.

Brown, P.A. (No Date) Innovative Metal Removal Technologies for Urban Stormwater. WERF Project No. 97-IRM-2. Retrieved October 29, 2001 from the World Wide Web: www.werf.org/research/search/

This study researches the mechanistic fate of metals found in urban stormwater runoff as they move through treatment systems (filtration systems and swales). Analysis and design guidance will be developed for innovative methods to improve existing treatment schemes and develop new ones.

Chesapeake Research Consortium. (1998) Nutrient Loading from Conventional and Innovative Site Development. Prepared by Center for Watershed Protection.

This study compares the nutrient export and economic benefits of conventional and innovative site planning techniques in the Chesapeake Bay watershed. Various development scenarios are assessed for differences in the amount of impervious cover, runoff and infiltration volumes, cost, and nitrogen and phosphorus output between conventional to innovative site design.

Construction Engineering Research Foundation, Environmental Technology Evaluation Center. (No Date) Performance Capabilities of Conventional BMPs. Retrieved October 22, 2001 from the World Wide Web: http://www.cerf.org/evtec/eval/erosion.htm

EvTEC tested blown straw for slope treatments and hay bale checks in channels for erosion and sediment control under field operating conditions. The testing took place between August and October 2000; final reports are under EPA review.

Construction Engineering Research Foundation, Environmental Technology Evaluation Center. (No Date) Tommy Silt Fence Machine. Retrieved October 22, 2001 from the World Wide Web: http://www.cerf.org/evtec/eval/tommy.htm

The Tommy Silt Fence Machine slices through soil and inserts silt fence without displacing the soil. Testing of the efficacy of the trenching and slicing method was completed in August 2000 at construction sites in Iowa.

Desbonette, A., P. Pogue, V. Lee, and N. Wolff. (1994) Vegetated Buffers in the Coastal Zone: A Summary Review and Bibliography. Coastal Resources Center. University of Rhode Island, 72 pp. Referenced in Stormwater Management Fact Sheet: Grassed Filter Strip. Retrieved October 25, 2001, from the World Wide Web: www.stormwatercenter.net

Dillaha, T.A., R.B. Renear, S. Mostaghimi, D. Lee. (1989) Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control. Transactions of the American Society of Agricultural Engineers 32(2):513-519. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001, from the World Wide Web: www.stormwatercenter.net

Dingfang Liu, Zheng Teng, and John J. Sansalone, Frank K. Cartledge. (2001) Surface Characteristics of Sorptive-Filtration Storm Water Media. I: Low-Density (P_s< 1.0) Oxide-Coated Buoyant Media. Journal of Environmental Engineering 127(10):868- 878.

Control strategies for storm water that combine unit operations and processes can offer distinct advantages for many in situ applications in the built environment. Examples include a variety of control strategies that utilize engineered buoyant media to provide filtration and adsorption for heavy metals transported by storm water. With the goal of producing such media, methods were developed to coat iron and manganese oxide onto the surface of common polymeric media. Surface characteristics of coating media were determined by powder X-ray diffraction, infrared spectroscopy, and scanning electron microscopy analyses. Results indicated that oxide coatings ranged from 20 to 200 µm in depth, and surface areas were increased from 0.05 m^2/g for uncoated spherical polymeric media to 27 m^2/g for the same media after oxide coating. All manganese oxide coated media generated a net negative surface charge in the typical storm water pH range of 6-8.

Doyle, R.C., G.C. Stanton, and D.C. Wolf. (1977) Effectiveness of Forest and Grass Buffer Filters in Improving the Water Quality of Manure Polluted Runoff. American Society of Agricultural Engineers, Paper No. 77-2501. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001, from the World Wide Web: www.stormwatercenter.net

Elzufon, Betsy. (1998) Residential and Commercial Source Programs to Meet Water Quality Goals. WERF Project No. 95-IRM-1. Retrieved November 6, 2001 from the World Wide Web: www.werf.org/research/search/

This study compiles and evaluates existing information on commercial and residential sources of waste water and storm water pollution. BMPs for a variety of commercial sources are described. Public education programs from around the U.S. and ways to measure their effectiveness are presented. Future research needs, including addressing cross-jurisdictional management issues, are presented.

Fan, Chi Yuan. (No Date) BMP Manual. USEPA/ORD/NRMRL/Urban Watershed Management Branch.

The OW-OWM has requested that the WWF Program finalize a guidance manual on the use of stormwater control BMPs to minimize cross-media transfer of contaminants during WWF conditions. Many BMPs have been produced without the benefit of past performance data; therefore a timely review of the performance and longevity of the most appropriate practices should be made to assist the user community. This guide will evaluate the relationship of storm flowrates and pollutant concentrations and other pertinent factors, e.g., BMP versus drainage area size ratio and soil infiltration capacity to BMP performance, especially the removal of toxic pollutants. It will also assess the effect of programmatic BMP (e.g., education for pesticide usage and waste-oil recycling), maintenance and safety considerations, applicable federal regulations, and computer modeling. Simple controls associated with development options including the effects of roof drain disconnections, pavement drainage disconnections, and grass filters will be addressed.

Fennessey, L.A.J., J.M. Hamlett, G. Aron, and D. LaSota. (2001) Changes in Runoff due to Stormwater Management Pond Regulations. J. Hydrol. Eng. 6(4):317-327.

A continuous simulation stormwater management model (with 33 years of historical precipitation) was used to determine how the design criteria from five different stormwater management pond ordinances changed the runoff from a 7.77 ha watershed following a hypothetical development scenario. All five evaluated ordinances required that the postdevelopment runoff rates from the site be less than or equal to the predevelopment runoff rates for each return period (a zero increase criteria). However, none of the five ordinances were effective at limiting the increase in runoff peak rates for the 1- and 2-year return periods for the annual runoff series, the 1-year return period for the annual exceedance (partial) runoff series duration, or more frequent precipitation events. To better control the lower frequency runoff events from stormwater ponds, the 1- and 2-year return periods should always be analyzed for a basin's design. Additionally, there was a radical change in the frequency of small and moderate runoff events occurring from the watershed following the hypothetical development.

Gallii, J. (1992) Referenced in Stormwater Management Fact Sheet: Infiltration Trench Retrieved February 19, 2001, from the World Wide Web: www.stormwatercenter.net.

Godrej, A.N., et al. (1999) Evaluating the Use of Constructed Wetlands in Urban Areas. WERF Project No. 92-NPS-1. Retrieved November 6, 2001 from the World Wide Web: www.werf.org/research/search/

This report presents data on the performance of a constructed wetland in the Washington, DC area, representing a non-arid urban environment. Performance in removing ammonia, nitrate, and TSS are presented. Data on the diversity of wetland species of several wetlands are also presented.

Li, James Y. and Barry J. Adams. (2000) Probabilistic Models for Analysis of Urban Runoff Control Systems. Journal of Environmental Engineering 126(3):217-224.

To analyze the performance of various combinations of runoff control systems, analytical probabilistic models were applied to analyze the runoff quantity/quality control performance of various combinations of storage and treatment systems. These analytical probabilistic models are developed with derived probability distribution theory whereby the input meteorology to the catchment is described by probability density functions (PDFs) of the meteorological characteristics that are transformed by hydrologic/hydraulic functions to PDFs of the system performance variables. The resulting PDFs are then used to determine the average performance conditions. These models provide closed-formed solutions of the performance equations that are highly efficient in both a conceptual and computational sense. As a result, they are particularly useful for the screening analysis of urban runoff control alternatives.

Lowrance, R.R., R.L. Todd, and L.E. Asmussen. (1983) Waterborne Nutrient Budgets for the Riparian Zone of an Agricultural Watershed. Agriculture, Ecosystems, and Environment 10:371-384. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

Lowrance, R.R., R.L. Todd, J. Fail, O. Hendrickson, R. Leonard, and L.E. Asmussen. (1984) Riparian Forests as Nutrient Filters in Agricultural Watersheds. Bioscience 34:374-377. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

Magette, W.L., R.B. Brinsfield, R.E. Palmer, J.D. Wood, T.A. Dillaha, and R.B. Reneau. (1987) Vegetated Filter Strips for Agriculture Runoff Treatment. United States Environmental Protection Agency Region III, Report #CBP/TRS 2/87-003314-01. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

McKenzie, D. and G. Irwin. (1988) Effects of Two Storm Water Management Methods on the Quality of Water in the Upper Biscayne Aquifer at Two Commercial Areas in Dade County, Fla. US Geological Survey: Water Resources Investigations Report 88-4069. U.S. Geological Survey, Denver, Colorado.

Minnesota Pollution Control Agency. (2000) Protecting Water Quality in Urban Areas. March.

> This manual contains detailed information about BMPs that can be used to protect lakes, streams and groundwater from stormwater-related pollution.

Overman, A.R. and T. Schanze. (1985) Runoff Water Quality from Wastewater Irrigation. Transactions of the American Society of Agricultural Engineers 28:1535-1538. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

Pitt, R. (No Date) The Risk of Ground Water Contamination from Infiltration of Storm Water Runoff. Technical note #34 from Water Protection Techniques 1(3):126-128.

Schiffer, D. (1989) Effects of Three Highway Runoff Detention Methods on Water Quality of the Surficial Aquifer System in Central Florida. U.S. Geological Survey: Water Resources Investigations Report 88-4170. Denver, Colorado.

Schwer, C.B. and J.C. Clausen. (1989) Vegetative Filter Treatment of Dairy Milkhouse Wastewater. Journal of Environmental Quality 18:446-451. Referenced in Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

Stormwater Manager's Resource Center. (No Date) Stormwater Management Fact Sheet: Grassed Filter Strip. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

This project provides a rough estimate of the cost of filter strips, based on the cost of seed or sod, in addition to the cost of the land.

Stormwater Manager's Resource Center. (2000a) Stormwater Management Fact Sheet: Infiltration Trench. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net

Stormwater Manager's Resource Center. (2000b) Stormwater Management Fact Sheet: Buffer Zones. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net.

Stormwater Manager's Resource Center. (2000c) Stormwater Management Fact Sheet: Grassed Filter Strip. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net.

Stormwater Manager's Resource Center. (2000d) Stormwater Management Fact Sheet: Storm Water Wetland. Retrieved October 25, 2001 from the World Wide Web: www.stormwatercenter.net.

Urban Water Resources Research Council. (No Date) National Storm Water Best Management Practices Database. Developed by the Urban Water Resources Research Council of ASCE under a cooperative agreement with EPA. Retrieved October 29, 2001 from the World Wide Web: http://www.bmpdatabase.org/index.html.

The database summarizes studies on the performance of BMPs in removing a variety of contaminants. Included are over 100 individual studies of the effectiveness of various structural measures in removal of a variety of contaminants such as heavy metals, nutrients, fecal coliform, and oil and grease removal.

Urbonas, Ben. (1997) Assessment of Stormwater Best Management Practice Effectiveness. *In*: Innovative Urban Wet-Weather Flow Management Systems. U.S. EPA Urban Watershed Management Branch. EPA-600-R-99-029.

This paper discusses the effectiveness of structural and nonstructural BMPs. Issues to consider in design to improve effectiveness. Rated as most effective: minimize impervious zones, extended detention basins, retention ponds, and wetlands.

U.S. EPA, Office of Ground Water and Drinking Water. (1998) Guidance on Storm Water Drainage Wells. Interim Final. May. Retrieved January 7, 2002 from the World Wide Web: http://www.epa.gov/r5water/storm/newstorm.htm.

This guidance describes BMPs for the siting, design, and operation of Class V storm water drainage wells.

U.S. EPA, Office of Ground Water and Drinking Water. (1999) The Class V Underground Injection Control Study. Volume 3: Storm Water Drainage Wells. EPA/816-R-99-014c. September 30. Retrieved January 7, 2002 from the World Wide Web: http://www.epa.gov/safewater/uic/classv/volume3.pdf

U.S. EPA, Office of Science and Technology. (1999) Preliminary Data Summary of Urban Stormwater Best Management Practices. EPA-821-R-99-012. August. Retrieved November 1, 2001 from the World Wide Web: www.epa.gov/OST/stormwater/

Topics covered include: BMP performance measures and measurable goals, availability of measurement methods, design criteria, monitoring issues, costs and cost minimization opportunities, and the benefits and economic impacts of constructing and operating BMPs. The discussion of BMP performance includes structural BMPs such as infiltration devices, ponds, filters and constructed wetlands; and the effectiveness of non-structural BMPs, low impact development practices and management measures such as maintenance practices, street sweeping, public education and outreach programs. Chapter 6 provides cost and benefit information, referenced from other studies, on various BMPs.

U.S. EPA, Office of Science and Technology. (2000) National Pollutant Removal Performance Database for Stormwater Treatment Practices. Second edition. Prepared by Rebecca Winer, Center for Watershed Protection. June.

This document assesses and compares the effectiveness of a variety of stormwater management measures in removing selected pollutants, including phosphorus, nitrogen, TSS, carbon, metals, bacteria, hydrocarbons. 139 data sheets are included.

Valeo, Caterina and Syed M.A. Moin. (2001) Hortonian and Variable Source Area Modeling in Urbanizing Basins. J. Hydrol. Eng. 6(4):328-335.

The conventional hydrological model QualHYMO, which uses infiltration excess overland flow as the primary mechanism for runoff generation, is compared with a variable source area model that was modified for use on urbanizing watersheds. The modified variable source area model is known as TOPURBAN, as it uses TOPMODEL concepts to generate saturation excess overland flow. TOPURBAN proved to provide better modeling efficiency than QualHYMO in four continuous modeling tests, and slightly better efficiency in two continuous modeling tests. QualHYMO was found to produce large overpredictions due to its representation of urban areas, and the assumption of the entire rural area contributing to flow when rural losses were exceeded. TOPURBAN slightly underpredicted peak flows, but other hydrograph characteristics were modeled well. TOPURBAN outperformed QualHYMO in applications to two single events with similar antecedent moisture conditions. TOPURBAN is considered by the writers to be a good predictor of flow rates for certain urbanizing catchments.

Van Buren, M.A., W.E. Watt, J. Marsalek, and B.C. Anderson. (2000) Thermal Balance of On-Stream Storm-Water Management Pond. Journal of Environmental Engineering 126(6):509-517.

A methodology and assessment of the thermal balance of an on-stream storm-water pond are documented for a test facility in Kingston, Ontario, Canada. An energy balance model was used to estimate average pond water temperature as a function of thermal energy stored in the pond. Major thermal energy fluxes considered within the pond system included radiant heating and cooling of the pond, evaporation, and thermal energy inflow from the upstream catchment and outflow from the pond. A thermal energy balance was achieved between thermal energy input and output measured over the field season. During dry-weather periods, pond temperature increased as a result of solar heating, and thermal energy input exceeded output. Conversely, during wet-weather periods, pond temperature decreased as a result of limited solar radiation and replacement of warm pond water by cool inflow water from the upstream catchment, and thermal energy output exceeded input. A series of discrete temperature surveys in the pond revealed that the location of the stationary temperature probe, used to measure pond temperature, resulted in an underestimation of the average pond temperature during dry- and wet-weather periods. However, this discrepancy was comparable to the difference between measured and modeled values, which further confirmed the model validity.

Wilde, F. (1994) Geochemistry and Factors Affecting Ground Water Quality at Three Storm Water Management Sites in Maryland. US Geological Survey Report of Investigations Number 59. U.S. Geological Survey, Washington, DC.

Winer, R. (2000) National Pollutant Removal Performance Data Base for Stormwater Treatment Practices: 2nd Edition. Center for Watershed Protection. Ellicott City, Maryland. Referenced in Stormwater Management Fact Sheet: Infiltration Trench. Retrieved October 25, 2001, from the World Wide Web: www.stormwatercenter.net

Yanbo, Li and Steven G. Buchberger. (1999) Variably Saturated Flow in Storm-Water Partial Exfiltration Trench. Journal of Environmental Engineering 125(6):556-565.

Storm water from impervious urban areas can adversely impact water quality and quantity. The partial exfiltration trench (PET) is a control device designed to moderate both the quality and the quantity of urban runoff. This paper uses a 2D numerical model to evaluate variably saturated flow profiles and residence time distributions for a PET subject to storm water loading. Parameters estimated from laboratory experiments and hydrographs measured at a prototype PET are used to calibrate the numerical model. Simulation experiments show that flow through the PET is influenced strongly by the rate and duration of the hydraulic loading and by the type and properties of the surrounding soil. Unless the surrounding soil is nearly saturated or highly impermeable, propagation of the wetting front through an unlined PET occurs as 2D variably saturated flow. Variably saturated 2D flow through the PET is characterized by skewed residence time distributions, long mean travel times (relative to plug flow), high exfiltration losses to the surrounding soil, and low tracer mass recovery at the underdrain. These features of the PET performance are beneficial for storm-water treatment because the first flush

Yu, S., S. Barnes, and V. Gerde. (1993) Testing of Best Management Practices for Controlling Highway Runoff. Virginia Transportation Research Council. FHWA/VA 93-R16, 60 pp. Referenced in Stormwater Management Fact Sheet: Grassed Filter Strip. Retrieved October 25, 2001, from the World Wide Web: www.stormwatercenter.net

Washington State Department of Transportation. Highway Runoff Manual. M 31-16. February 1995.

This technical manual is a guide to design and operation of transportation facilities that can affect stormwater runoff. Chapter 7 discusses highway maintenance including maintaining stormwater facilities, snow and ice removal, and disposal of wastes generated on highways. Chapter 8 describes sediment control and water quality and quantity BMPs. The manual defines each BMP and provides general criteria, design procedures, and construction and maintenance criteria for each listed.

Yiping Guo. (2001) Hydrologic Design of Urban Flood Control Detention Ponds. J. Hydrol. Eng. 6(6):472-479.

Three different approaches can be used for the hydrologic design of flood control detention ponds that service urban catchments: (1) design storm approach; (2) continuous simulation approach; and (3) analytical probabilistic approach. In this study, the three approaches were compared for the first time using a hypothetical catchment in Chicago, Illinois. While all three approaches can generate similar results, the results from the design storm approach were shown to vary by 40% to 50% depending on the choice of models and design storms. An appreciation of this level of variation of the results and the development of procedures for the reduction of this variation are recommended for better application of the design storm approach. The results presented in this paper further verify the suitability of the analytical probabilistic approach for the hydrologic design of urban flood control detention ponds.

Ongoing Research

No studies were identified as ongoing.

Septic Systems

Recent Research

Bastian, R.K. and D.A. Hammer. (1993) The Use of Constructed Wetlands for Wastewater Treatment and Recycling. *In:* Constructed Wetlands for Water Quality Improvement, G.A. Moshiri (Editor). pp. 59-68. CRC Press, Boca Raton, Florida.

Bastian, R.K., P.E. Shanaghan, and B.P. Thompson. (1989) Use of Wetlands for Municipal Wastewater Treatment and Disposal - Regulatory Issues and EPA Policies. *In:* Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural, D.A. Hammer (Editor). Lewis Publishers, Chelsea, Michigan.

Best Management Practices to Protect Water Quality. Retrieved from the World Wide Web: http://www.nalms.org/bclss/septic.html

> The British Columbia Lake Stewardship Society compiled a fact sheet on septic system best management practices. This fact sheet lists BMPs for septic systems, and advantages and disadvantages

Corbitt, R.A. and P.T. Bowen. (1994) Constructed Wetlands for Wastewater Treatment. *In*: Applied Wetlands Science and Technology, D.M. Kent (Editor). pp. 221-241. Lewis Publishers, CRC Press, Boca Raton, Florida, 436 pp.

Dipankar, Sen and Donald Schwinn. (1997) Case Histories of Innovative Approaches to Nitrogen Removal Without New Tankage. WEFTEC '97 Water Environmental Federation Conference Proceedings Vol. 1

Dunkelberger, A. Haub, E. Murphy, M. Petrie, L. Velez, P. Wickham, and R. Mead . (1997?) Septic Systems Assessment Project: Managing Septic Systems in an Urbanizing Environment 1997. (National Small Flows Clearinghouse).

> The SSAP takes a broad look at septic systems in the Olympia area. It gathers local on-site sewage system (OSS) data, and reviews the major OSS ground water impact studies that have occurred in Washington State and the rest of the nation. The SSAP includes a ground water monitoring, pilot project. The monitoring component is designed to determine whether indications of adverse OSS impacts to ground water exist, and to assess the value of continued ground water monitoring for OSS impacts.

Ehrenfeld, J.G. (1987) The Role of Woody Vegetation in Preventing Ground Water Pollution by Nitrogen from Septic Tank Leachate. Water Resources 21(5):605-614.

Hammer, D.A. (Editor). (1989) Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Chelsea, Michigan, 831 pp.

Moshiri, G.A. (Editor). (1993) Constructed Wetlands for Water Quality Improvement. Lewis Publishers, CRC Press, Boca Raton, Florida, 632 pp.

North Carolina State University published a report on septic systems best management practices: http://h2osparc.wq.ncsu.edu/estuary/rec/septic.html

Sand Filter Trenches for Purification of Septic Tank Effluent: II. The Fate of Nitrogen. (1981) Journal of Environmental Quality 10(3).

Tchobanoglous, George. (1998) Decentralized Wastewater Management: Water Resources and the Urban Environment. ASCE.

> Topics to be examined include: (1) the need for decentralized wastewater management, (2) the elements of decentralized systems, (3) the role and importance of technology, (4) the importance of effective management for decentralized systems, and (5) the economics of decentralized systems, and (6) the future for decentralized systems.

Tchonbanoglous, G. and F. Burton. (1991) Wastewater Engineering: Treatment, Disposal, and Reuse. 3rd Edition, Metcalf and Eddy, New York, NewYork: McGraw-Hill

The Management of Privately-Owned (On-Site) Wastewater Treatment Systems. (1994) The National Onsite Wastewater Recycling Association Presents: Management, Testing and Evaluation: Today and Tomorrow. Proceedings of the 1994 Annual Conference, Atlanta, Georgia.

> This acticle presents a revised management system for Privately Owned Wastewater (On-Site)Treatment Systems (POWTS) in Wisconsin. The management system proposed are simple in concept but challenging in practice. The proposed system selects the best of the existing systems and eliminates the worst. A database will be used to house all the information after the code goes into effect. The model used for this system will be highly sophisticated and is believed to be adopted nationwide in the future.

The Texas On-site Wastewater Treatment Research Council: http://towtrc.tamu.edu/navigation/general-info-overview.html

> The Council awards competitive grants and contracts to support applied research, demonstration projects, and information transfer regarding on-site wastewater treatment. The Council is not an advisory council and does not regulate the on-site industry in the State of Texas.

The Consortium of Institutes for Decentralized Wastewater Treatment:
http://www.onsiteconsortium.org/

The “Consortium" is a group of Educational Institutions cooperating on decentralized wastewater training and research efforts. The Consortium also includes people from educational institutions, citizens groups, regulatory agencies and private industry.

U.S. EPA. (1992) An Overview and Research Bibliography for Reducing Nitrogen Loadings from Septic Systems. Boston: WCB/McGraw-Hill.

U.S. EPA. (2000) Guidelines for Management of Onsite/Decentralized Wastewater Systems - Draft September 2000. Retrieved from the World Wide Web:
http://www.epa.gov/owm/decent/index.htm

EPA is proposing the voluntary national guidelines in order to raise the quality of management programs, establish minimum levels of activity, and institutionalize the concept of management. Implementation of the guidelines will help communities meet water quality and public health goals, provide a greater range of options for cost-effectively meeting wastewater needs, and protect consumers’ investment in home and business ownership. These guidelines contain a set of model programs, based on a comprehensive approach that relies on coordinating the responsibilities and actions among the State, tribal or local regulatory agency, the management entity or service provider and the system owner(s). These model programs are structured to reflect an increasing need for more comprehensive management as the sensitivity of the environment and/or the degree of technological complexity increases. A program’s designation increases progressively from Model Program 1 through Model Program 5, reflecting the increased level of management activities needed to achieve water quality and public health goals.

U.S. EPA. (2002) Onsite Wastewater Treatment Systems Manual. Prepared by Office of Water and Office of Research and Development. EPA 625/R-00/008. February.

This manual provides the latest information on onsite system management, siting, design, installation, maintenance, monitoring and replacement. The manual is designed to help users assess and select the best and most suitable sets of technologies and techniques that are appropriate for local site specific conditions. The manual was written to promote the use of an integrated risk/performance-based approach to OWTS design. Information on OWTS cost and effectiveness has been included.

U.S. EPA, OWM: http://www.epa.gov/owm/mtbfact.htm

EPA published a set of fact sheets on municipal technologies, including decentralized systems technology, in September of 2000. These fact sheets describe different aspects of the technology: These fact sheets do not address the effectiveness of management practices.

U.S. EPA. (1999) The Class V Underground Injection Control Study. Washington, DC. EPA/916-R-99-014.

Wall, D.B. (1991) Septic Systems: Contributions to Ground Water Nitrogen and Best Management Practices to Reduce Nitrogen Contamination. *In*: Nitrogen in Minnesota Ground Water. St. Paul, Minnesota: Minnesota Pollution Control Agency, Chapter 1.

Weider, R.K., G. Tchobanoglous, and R.W. Tuttle. (1989) Preliminary Considerations Regarding Constructed Wetlands for Wastewater Treatment. *In:* Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural, D.A. Hammer (Editor). Lewis Publishers, Chelsea, Michigan, pp. 297-305.

Yates, M.V. (1987) Septic Tank Siting to Minimize the Contamination of Ground Water by Microorganisms. U.S. EPA, Office of Ground Water Protection, Washington, DC.

Yates, M.V. and S.R. Yates. (1989) Septic Tank Setback Distances: A Way to Minimize Virus Contamination of Drinking Water. Ground Water 27(2):202-208.

Ongoing Research

Burks, B.D. (2002) Advancements in Individual Sewage Disposal Systems. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 66-67.

Concerns about ground water quality are being reflected in revised state and local sanitary codes, new codes list ground water protection standards. Private industry is developing and implementing design processes and products to meet these emerging effluent quality standards. Private industry are developing design and product solutions to address nitrogen, phosphorus, and fecal coliform contamination. Studies examining the performance and reliability of these designs and products will be examined.

Above-Ground Storage Tanks

Recent Research

American Petroleum Institute. (1998) A Survey of Diked-Area Liner Use at Aboveground Storage Tanks Facilities. API 341, 32 pp. Retrieved January 21, 2002 from the World Wide Web: http://www.techstreet.com/cgi-bin/detail?product_id=55744

In 1997, API conducted a survey designed to evaluate the effectiveness of diked-area liner systems and to document operational problems involved with their use. The survey data

indicated that the effectiveness of liners in protecting the environment is limited because liner systems frequently fail. The data further showed that there are few releases from aboveground storage tanks that would be addressed by diked-area liners. Because there were few releases, the data do not directly demonstrate the effectiveness or ineffectiveness of liner systems in containing releases; however, it was concluded that measures that prevent aboveground storage tank releases are more effective in protecting the environment and are more cost-effective in the long run.

American Petroleum Institute. (1994) An Engineering Evaluation of Acoustic Methods of Leak Detection in Aboveground Storage Tanks. Publ 322.

This report describes a set of controlled experiments conducted on a 40-ft. diameter refinery tank to determine the nature of acoustic leak signals and ambient noise under a range of test conditions. The features of a leak detection test needed for high performance are explored. The report concludes that accurate and reliable leak detection of aboveground storage tanks can be achieved through the use of acoustic methods.

American Petroleum Institute. (1994) An Engineering Evaluation of Volumetric Methods of Leak Detection in Aboveground Storage Tanks. Publ 323.

Two volumetric approaches to detecting leaks from aboveground storage tanks—precision temperature sensors and mass measurement approaches—are evaluated in this report. A set of controlled experiments on a 117-ft. diameter refinery tank is used to examine the effects of differential pressure on conventional level and temperature measurement systems. The features of a leak detection test needed for high performance are also explored.

American Petroleum Institute. (1994) An Evaluation of a Methodology for the Detection of Leaks in Aboveground Storage Tanks. Publ 325.

This report describes the results of the fourth phase of a program to define and advance the state of the art of leak detection for aboveground storage tanks (ASTs). Three leak detection technologies are examined—passiveacoustic, soil-vapor monitoring, and volumetric—over a wide range of tank types, petroleum fuels, and operational conditions. This study also assesses the applicability of a general leak detection methodology involving multiple tests and product levels as well as determines the integrity of 14 ASTs using two or more test methods.

American Petroleum Institute. (1993) Assessment of Tankfield Dike Lining Materials and Methods. Publ 315.

To assess tankfield materials and methods of containment, API commissioned a review of environmental regulations as well as a survey of candidate liner materials and installation methods to explore the technology base. The study was limited to diked areas surrounding storage tanks. Liner installations for secondary containment underneath tanks were excluded.

American Petroleum Institute. (1992) Estimated Costs and Benefits of Retrofitting Aboveground Petroleum Industry Storage Tanks with Release Prevention Measures. API 065 Retrieved January 21, 2002 from the World Wide Web: http://www.techstreet.com/cgi-bin/detail?product_id=24949

National Association of Corrosion Engineers. (2001) Standard Recommended Practice - Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks. ANSI/NACE RP0388-2001, 12 pp. Retrieved January 21, 2002 from the World Wide Web: http://www.techstreet.com/cgi-bin/detail?product_id=932536

Presents procedures and practices used in providing impressed current cathodic protection to the normally submerged steel surfaces inside water storage tanks. Recommendations for the design and installation of cathodic protection systems and methods for determining the effectiveness of these systems are also given.

U.S. EPA. (1996) EPA Liner Study: Report to Congress. Office of Solid Waste and Emergency Response Publication 9380.0-24.

EPA looked at two types of liner systems: (1) liners within secondary containment areas; and (2) double bottoms for vertical ASTs. EPA examined the environmental effectiveness and installation cost for various lining designs and facility types. For large facilities, it may cost 30-50% less to install a complete liner systems during the initial construction of a facility than to add a liner to an existing facility. However, new and existing small facilities should not find significant differences for liner installation costs.
EPA also found that maintenance of liners is essential to their continued effectiveness in limiting contamination. Some facility owners may not devote sufficient resources to ensuring that liner systems remain fully functional.

U.S. EPA. (1995?) Analysis of the Effectiveness of EPA's SPCC Program on Spill Risk. Retrieved January 21, 2002 from the World Wide Web: http://www.epa.gov/oilspill/spcc/pap_eff.pdf

In April 1995, EPA conducted a national survey of oil storage facilities potentially subject to its Spill Prevention, Control and Countermeasures (SPCC) regulation (40 CFR Part

112). The results of the analysis point to several conclusions about the SPCC program. First, the analysis shows that compliance with several specific SPCC provisions appears to reduce both the number and volume of spills, as well as the amount of oil that migrates outside of the facility's boundaries. Facility practices such as tank leak detection, spill overfill protection, pipe external protection, and secondary containment, also appear to reduce the number and magnitude of oil spills.

U.S. EPA. (1995?) Compliance Assistance Guide: SPCC Requirements and Pollution Prevention Practices for Bulk Storage Facilities. Retrieved January 22, 2002 from the World Wide Web: http://www.epa.gov/oilspill/spcc/bulk.pdf

This guide describes the equipment and operations considerations that must be addressed in an SPCC plan for an oil bulk-storage facility. The document also describes recommended practices for preventing pollution and discharges of oil, and discusses facility response plan applicability.

U.S. EPA. (No Date) AST and UST Outreach Guide. EPA Emergency Response Division - Final Draft.

The purpose of this guide is to clarify both sets of regulations (UST and AST) to ensure that all tanks are properly managed and to better protect our natural resources. This clarification will make it easier for facility and/or tank owners operators to determine whether their facilities are regulated, which regulations apply, and their responsibilities under the applicable regulations.

Ongoing Research

No ongoing research has been identified.

Underground Storage Tanks

Recent Research

American Petroleum Institute. (2001) Interior Lining of Underground Storage Tanks. API 1631, 35 pp. Retrieved January 21, 2002 from the World Wide Web: http://www.techstreet.com/cgi-bin/detail?product_id=913787

Provides minimum recommendations for the interior lining of existing steel and fiberglass reinforced plastic underground tanks used to store petroleum-based motor fuels and middle distillates. Recommendations and procedures to be followed by contractors, mechanics, and engineers are presented. Methods for vapor-freeing tanks, removing sediment, and cleaning interior surfaces of steel and fiberglass tanks are also presented, as are guidelines for identifying tanks that maybe lined.

American Petroleum Institute. (1996) Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems, 3rd Edition. API 1632. Retrieved January 21, 2002 from the World Wide Web: http://www.techstreet.com/cgi-bin/detail?product_id=3471

Covers two methods of providing cathodic protection for buried steel petroleum storage and dispensing systems. Provides information specific to buried steel structures such as motor fuel storage tanks and delivery piping waste oil tanks, heating-oil tanks, and automobile lifts installed at service stations.

Boulder Area Sustainability Information Network (BASIN). Leaking Underground Storage Tanks. Funded through EPA Environmental Monitoring for Public Access and Community Tracking (EMPACT) Program. Accessed January 22, 2002 from the World Wide Web: http://bcn.boulder.co.us/basin/waterworks/lust.html#contaminants

Website devoted to providing information to local community about leaking storage tanks. Includes sections on Federal regulations, and contaminant properties.

Coe, B. (2002) Use of Fiberglass Underground Storage Tanks for Watertight Containment of Onsite Wastewater Treatment in Fractured Bedrock and other Sensitive Water Table Environments. In: Fractured-Rock Aquifers 2002, March 13-15, 2002, Denver, Colorado. Pg. 61.

National Work Group on Leak Detection Evaluations. (2001) List of Leak Detection Evaluations for UST Systems, 9th Edition. U.S. EPA Office of Underground Storage Tanks Publication. Retrieved January 22, 2002 from the World Wide Web: http://www.epa.gov/OUST/pubs/ldlist9.pdf

This 300+ page reference manual contains a summary of specifications, based on third-party evaluations, for over 275 systems that detect leaks from USTs and their piping. Each summary provides information on such items as certified detectable leak rate/threshold, test period duration, product applicability, calibration requirements, restrictions on the use of the device, and so on.

Ongoing Research

Construction Engineering Research Foundation, Environmental Technology Evaluation Center. (No Date) Low Range Differential Pressure (LRDP) Leak Detection Technology. Retrieved October 22, 2001 from the World Wide Web: http://www.cerf.org/evtec/eval/lrdp.htm

This UST leak detection system is a mass-based, leak detection and monitoring system can detect small leaks in bulk (large-capacity) USTs. It was developed by Vista Research, Inc. and the Naval Facilities Engineering Service Center. Participants at a workshop recommended further study of testing protocols for ASTs, a study of the applicability of

this technology to ASTs, education for end-users of the technology, and updating existing information on recent technology modifications to USTs/ASTs such as evaluations of single- vs. double-walled piping systems and double-walled AST bottoms.

University of California at Davis. Guidance Manual on Minimizing MTBE and Other Fuel-Related Contaminants in Lakes and Reservoirs. AWWARF Project No. 2705. Research partner: Contra Costa Water District. To be completed in 2002.

This project will model methyl tertiary butyl ether (MTBE) and other organic compounds (specifically, benzene, toluene, ethylbenzene, and xylenes [BTEX]) in lakes and reservoirs and calibrate this model in two reservoirs. Also will investigate several options for controlling MTBE and other fuel-related contaminants in water bodies. Will develop a guidance manual for water utilities and agencies for minimizing the impacts of MTBE and other contaminants in surface waters.

Vehicle Washing

Recent Research

Battelle Institute, Columbus Labs. (1996) Power Washer With Wastewater Recycling Unit. May. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/FEDFUND/EPA/Epastd/POWERWAS.html

The Seattle Metro uses power washing to clean parts for the metropolitan area mass transportation busses. The washing system produces four waste streams: wastewater, settled particulate matter/ sludge, skimmer/flotation waste, and a small amount of steam. This study analyzed a high-pressure, high-temperature cleaning unit with a wastewater recycling system.

Horner, R. R. and S. R. Wonacott. (1985) Performance Evaluation of a Detention Basin and Coalescing Plate Oil Separator for Treating Urban Stormwater Runoff. Washington State University, Publication A-130. June.

Oregon DEQ. (1998) DEQ Storm Water Management Guidelines. February. Retrieved January 10, 2002 from the World Wide Web: http://www.deq.state.or.us/wq/groundwa/swmgmtguide.htm

U.S. EPA, Office of Ground Water and Drinking Water. (1999) The Class V Underground Injection Control Study, Volume 4. Wells that Inject Fluids from Carwashes Without Engine or Undercarriage Cleaning. September 30. Retrieved January 9, 2002, from the World Wide Web: http://www.epa.gov/safewater/uic/classv/volume4.pdf

U.S. EPA, Office of Water. (1992) Class V BMP Fact Sheet Number 3. 570/9-91-036L. January.

U.S. EPA, Office of Science and Technology. (2000) National Pollutant Removal Performance Database for Stormwater Treatment Practices. Second edition. Prepared by Rebecca Winer, Center for Watershed Protection. June.

> This document assesses and compares the effectiveness of a variety of stormwater management measures in removing selected pollutants, including phosphorus, nitrogen, TSS, carbon, metals, bacteria, hydrocarbons. 139 data sheets are included.

Ongoing Research

No studies have been identified as ongoing.

Small Quantity Chemical Use, Storage, and Disposal

Recent Research

Health Care Without Harm. (No Date) Going Green: A Resource Kit for Pollution Prevention in Health Care. http://www.noharm.org/index.cfm?page_ID=29

> This resource kit can assist health care providers/administrators in their efforts to reduce health care industry pollution from their facilities. It contains simple to complex steps that will have a measurable impact on environmental performance.

Michigan Technological University. (1996) Environmentally Conscious Design and Manufacturing. October. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/FEDFUND/EPA/EPAEED/ENVIRON3.html

> The overall goal of this project is to develop environmentally conscious design and manufacturing tools and methods that will help alleviate the abundance of waste associated with used product and manufacturing waste streams. Environmentally conscious design focuses efforts on determining product design specifications, developing and analyzing design features, and evaluating costs and benefits.

Minnesota Center for Environmental Advocacy. (1998) Partnering to Reduce Medical Product Toxicity. September. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/MINN_OEA/PARTNERI.html

> The Minnesota Center for Environmental Advocacy (MCEA) proposes to reduce the release of toxic substances to the environment from the production, use and disposal of medical products. MCEA will work with Minnesota health care providers to adopt and implement pollution prevention-oriented purchasing policies which call for the substitution of less environmentally harmful products.

Minnesota Valley Engineering, Inc. (1998) Liquid CO_2 Machine Dry Cleaning Test. September. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/MINN_OEA/LIQUIDCO.html

> Minnesota Valley Engineering, Inc. will install and test a beta prototype liquid CO_2 machine in a dry cleaning environment. They will evaluate the machine's performance compared to three other dry cleaning processes: aqueous, perchloroethylene (perc), and petroleum.

North Carolina Division of Pollution Prevention and Environmental Assistance. (1996) Water and Chemical Conservation Through Installation of Ultra Tandem 65k/12 Tunnel Washer. December. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/NC_OWR/WATERAND.html

> Maple Springs Laundry installed a Ultra Tandem 65k/12 Tunnel Washer, manufactured by Boewe Passat, to replace the current Milner 450 rapid load washers. The UT 65k/12 will reduce water consumption per pound of linens from approximately 3.8 gallons to 1 gallon.

NuLife Dry Cleaners Inc. (1998) Dry Cleaning in the 21st Century: Toxicity and Hazard Elimination. September. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/MINN_OEA/DRYCLEAN.html

> This project will demonstrate the feasibility of having dry wash or CO2-based (non-hazardous waste producing, non-ozone-depleting, non-toxic, non-flammable) dry cleaning technology while at the same time improving cleaning performance. For small businesses, this can prove to be a positive model to build on for other similar industries.

Pacific Northwest Pollution Prevention Resource Center. Pollution Prevention Research Projects Database. Available on the World Wide Web: http://www.pprc.org/pprc/rpd/rpdsearch.cfm

Tri-Star Technologies Co., Inc. (1998) Demonstration of Printwise: A "Near-Zero" Lithographic Ink and Blanket Wash System. June. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/TURI/demonstr.html

> This report presents the results of a demonstration of the Printwise lithographic ink and water-based presswash printing system, designed to significantly reduce VOC emissions. The system employs vegetable oil-based ink containing a "solubility conversion mechanism" that reacts with the presswash to become water-soluble.

T.S. Designs, Inc. (1997) Recycling of Wash Water for Reclaiming Screens in a Textile Silk Screen Printing Operation. April. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/NC_OWR/Recyclin.html

> This project examines the potential to collect, filter, and recycle screen reclaim solution. This project investigated the potential to collect the water in a tank fitted with a recirculating filter and to reuse the rinse water. The new system effectively removes the emulsion, and the rinse water can be reused for approximately one month.

University of California, Los Angeles, Pollution Prevention Education and Research Center. (1996) Wet Cleaning Demonstration Project. December. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/UCLA/WETCLEAN.html

> New technologies such as "wet cleaning" have the potential to significantly reduce or even eliminate the use of dry cleaning chemicals. PPERC is working in cooperation with a U.S. EPA-sponsored wet cleaning demonstration and research project in Chicago, IL. The findings of this research will be used to educate the local dry cleaning industry about wet cleaning alternatives and encourage the use of non-toxic alternatives.

University of Tennessee. (1996) Clean Technology Demonstrations for the 33/50 Chemicals. April. EPA/600/R-95/120. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/FEDFUND/EPA/Epastd/CLEANTEK.html

> Technologies evaluated as alternatives to trichloroethylene vapor degreasing were aqueous washing, no-clean technology, and a hot water wash system. Test results showed an improvement in cleaning performance with the aqueous alternative and the same performance with the no-clean alternative.

University of Texas at Austin. (1998) Waste Minimization of Volatile Organic Compounds by Microwave Regeneration of Adsorbents. April. Retrieved January 22, 2002 from the World Wide Web: http://www.pprc.org/pprc/rpd/STATEFND/GULFCOAS/wastemi2.html

> A pilot project has been initiated to investigate recovery of VOCs by regenerating adsorbents with microwave dielectric heating. This technique could be applicable to a variety of operations from dry cleaners and gas stations to petrochemical production facilties.

U.S. EPA. (1998) Frequently Asked Questions About Drycleaning. EPA 744-K-98-002. June. Retrieved January 23, 2002 from the World Wide Web: http://www.epa.gov/dfe/pubs/garment/ctsa/factsheet/ctsafaqcopy.htm

Washington State Department of Ecology. (1995) Auto Body Restoration and Painting: A Success Story in Waste Reduction 1992-93. November. Retrieved January 23, 2002 from the World Wide Web: http://es.epa.gov/techinfo/facts/washington/wsde5.html

This is a waste reduction success story about a small business auto body repair shop in Puyallup, Washington. Topics include the driving force behind the company's waste reduction success, including the use of less toxic paints, savings in company liability, and quick pay-back period. By using less toxic paints and recycling solvents, the shop reduced liability and saved $4,800 per year in waste management costs.

Wisconsin Department of Natural Resources. (1996) Case Study: Equipment Improvement Cuts Drycleaning VOC Emissions by 80%. March. Retrieved January 23, 2002 from the World Wide Web: http://es.epa.gov/program/regional/state/wi/spicspan.html

This is an Enviroene case study on installation of new dry cleaning equipment that reduced volatile organic compound (VOC) emissions.

Ongoing Research

No studies were identified as ongoing.

Animal Feeding Operations

Recent Research

Adam, R., R. Lagace, and M. Vallieres. (1986) Evaluation of Beef Feedlot Runoff Treatment by a Vegetative Filter. American Society of Agricultural Engineers, Paper No. 86-208. St. Joseph, Michigan.

Allen, G., A. Lovell, B. Schwart, R. Lacewell, J. Schmucker, D. Leatham, and J. Richardson. (1991) Cost and Economic Feasibility of Dairy Waste Management: Central Texas Representative Dairies. Texas Agricultural Extension Service 11(4):8.

Baldwin, A.H. (1997) Managing Dairy Waste Using Constructed Wetlands and Composting. Research Projects, Northeast Region. Project Number: LNE95-62: Sustainable Agriculture Research and Education. 23 pp.

Barker, J.C. and J.P. Zublena. (1996) Components of a Complete Manure Management Plan. Publication Number EBAE 185-93. North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, North Carolina.

Barrington, S.F. and R.S. Broughton. (1988) Designing Earthen Storage Facilities for Manure Storage. Canadian Agricultural Engineering 30:289-292.

Barrington, S.F., R. Stilborne, and R.G. Moreno. (1995) Organic Liners for the Sealing of Earthen Reservoirs. Bioresource Technology 52(2):101-107. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/poultry.html

> Soil laboratory columns are used to test the sealing efficiency of organic liners made of various combinations of straw and either beef lot manure or broiler litter. The liquid and contaminant seepage-rate for each liner was monitored throughout the experiment. The liner made of 85% beef lot manure and 15% straw, on a dry matter basis, gave the lowest seepage rate.

Bekkers, K. (1996) Alternatives Calf Housing – Greenhouses. Agriculture and Marketing Newsletter 6(7). Retrieved January 4, 2002 from the World Wide Web: http://agri.gov.ns.ca/news/1996/vol6_7/calfhous.htm

Benham, B.L. and C.R. Mote. (1999) Investigating Dairy Lagoon Effluent Treatability in a Laboratory-Scale Constructed Wetlands System. Transaction of the American Society of Agricultural Engineers 42(2):495-502. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/conwet2.html

> Dairy lagoon supernatant treatability was evaluated using 10 laboratory-scale constructed wetlands. Selected design and operational variables were examined. Tested treatments were combinations of three organic loading rates (high, medium, and low) and three types of microbial attachment sites (vegetated, inert, and none). Removal efficiencies were based on analysis of influent/effluent waste constituent levels. Results showed consistently high nitrogen-removal efficiencies (65 to 81%) for all treatments. Carbon removal was less efficient (6 to 39%), and varied with influent strength.

Bohn, C.C. and J.C. Buckhouse. (1986) Effects of Grazing Management on Streambanks. Wildlife Management Institute. Transactions of the North American Wildlife and Natural Resources Conference (51st): Washington, DC, pp. 265-271. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9332.html

Borer, R.E., J.H. Pries, R.A. Clarke, and R.L. Knight. (1996) Assessing the Effectiveness of Treatment Wetland System for Pollutant Removal from Livestock Operations in the Southern United States. *In*: Proceedings of the Second National Workshop on Constructed Wetlands for Animal Waste Management, P.J. DuBowy (Editor). May 15-18, 1996, Fort Worth, Texas.

Brinton, W.F. (1990) Agricultural Waste Management and Composting. Woods End Res. Lab., American Society of Agronomics, Northeast Annual Meeting, University of New Hampshire.

Brion, Gail Montgomery and Huazhong H. Mao. (2000) Use of Total Coliform Test for Watershed Monitoring with Respect to Atypicals. Journal Environmental Engineering 126(2):175-181.

A 2-year study was conducted on the relationships between atypical colonies (AC) from total coliform (TC) tests and other bacterial indicators of water quality in a watershed mainly impacted by agricultural and urban animals. Eight representative sites were monitored for TC, feel coliforms (FC) and coliphage (CP) concentrations. Sampling sites included those impacted by raw sewage, agricultural runoff, urban runoff, and a mixture of urban and agricultural runoff. AC were found to be composed of coliforms (about 27%), noncoliforms (37%), and Aeromonas (36%). There was a clear pattern among the atypical concentrations, fecal pollution sources, and pollution levels. Correlation analyses found the densities of AC to be well associated with the densities of FC and not well associated with total CP (R_{FC} = 0.796 and R_{CP} = 0.575, respectively). A reference index defined as the ratio of AC to CP correlated well with degree of fecal pollution known to impact the sites. Results suggest that AC from TC tests using the membrane filter method and M-Endo medium may be used as supplemental indicators in conjunction with other microbial indicators for watershed monitoring.

Brown, M.P., P. Longabucco, M.R. Rausch Rafferty, P.D. Robillard, M.F. Walter, and D.A. Haith. (1989). Effects of Animal Waste Control Practices on Nonpoint-Source Phosphorus Loading in the West Branch of the Delaware River Watershed. Journal of Soil and Water Conservation 44(1):67-70. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

Results indicated that runoff from the West Branch watershed during the winter-spring period accounted for more than 80% of the annual loading of dissolved and total P to the reservoir. Reductions in barnyard P losses of 50% to 90% were shown to be achievable using practices that reduced the volume of runoff from these areas. However, the contribution of P from barnyard runoff was substantially less than that from manure-spread cropland in the budget for annual losses of dissolved and total P in the West Branch watershed. Manure spreading schedules that guide the location and timing of spreading had the potential to reduce P loading from the studied subwatershed by as much as 35% in the absence of short-term or long-term manure storage systems. Because treatment of cropland was given only limited attention, P loading reduction attributable to the program as well as the reservoir's water quality were negligible.

Buckhouse, J.C. and W. Elmore. (1997) Grazing Practice Relationships: Predicting Riparian Vegetation Response from Stream Systems. *In*: Watershed Management Guide for the Interior Northwest, T.E. Bedell and M.M. Borman (Editors). Extension Manual 8436: Oregon State University, Extension Service, Corvallis, Oregon, pp. 47-52.

CAST. (1996) Integrated Animal Waste Management. Task Force Report No. 28. Council for Agricultural Science and Technology, Ames, Iowa.

Cathcart, T., D. Hammer, and S. Triyono. (1994) Performance of a Constructed Wetland - Vegetative Strip System Used for Swine Waste Treatment. *In*: Constructed Wetlands for Animal

Waste Management, P. DuBowy and R. Reaves (Editors). Proceedings of workshop sponsored by the Conservation Technology Information Center, the US Department of Agriculture Soil Conservation Service, U.S. Environmental Protection Agency Region V, and Purdue University Research Program, April 4-6, 1994.

Chapman, S.L. (1996) Soil and Solid Poultry Waste Nutrient Management and Water Quality. Poultry Science, Poultry Science Association, Inc. 75(7):862-866. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/poultry.html

> Concerns about the impacts of nitrogen, phosphorus, and pathogens on surface and ground water quality has forced the poultry industry to implement voluntary waste management guidelines for use by growers. Strategies that growers may use to properly dispose of poultry waste include: 1) local land application as a fertilizer; 2) offsite marketing for use as a fertilizer or soil amendment, feed additive, or energy source; and 3) chemical additives that will immobilize nitrogen and phosphorus in the manure or litter. If properly followed, these and other innovative strategies should be adequate to protect surface and ground water quality without adversely affecting the economics of poultry production.

Chastain, J., W. Lucas, J. Albrecht, J. Pardue, J. Adams, and K. Moore. (1998) Solids and Nutrient Removal from Liquid Swine Manure Using a Screw Press Separator. American Society of Agricultural Engineers, Paper No. 98-4110. St. Joseph, Michigan.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, Jr., and D.J. Nichols. (1994) Effectiveness of Vegetative Filter Strips in Retaining Surface-applied Swine Manure Constituents. Transactions of the American Society of Agricultural Engineers 37:845-850. Abstract retrieved January 18, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9605.html

> Simulated rainfall was used to evaluate the effectiveness of vegetative filter strips (VFS) of varying lengths in reducing sediment and nutrient losses from plots treated with liquid swine manure. Mass transport of ammonia nitrogen, total Kjeldahl nitrogen, ortho-phosphorus, total phosphorus, and total suspended solids was reduced significantly by fescue VFS. The 3 and 21 m VFS removed 65 and 87% of incoming TKN, 71 and 99% of incoming NH_3-N, 65 and 94% of incoming PO_4-P, and 67 and 92% of the incoming TP, respectively. Effectiveness of VFS, however, did not increase significantly beyond 3 m for TSS and chemical oxygen demand and averaged 61 and 50%, respectively. Mass transport of TKN, NH_3-N, PO_4-P, and TP was minimized at the 9 m VFS length. The VFS did not significantly reduce nitrate nitrogen and fecal coliform from the incoming runoff. First-order kinetics described the removal of manure constituents.

Chaubey, I., D.R. Edwards, T.C. Daniel, and P.A. Moore, Jr. (1995) Buffer Strips to Improve Quality of Runoff from Land Areas Treated with Animal Manures. *In*: Animal Waste and the

Land-water Interface. Lewis Publishers, Boca Raton, Florida, pp. 363-370.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, Jr., and D.J. Nichols. (1995) Effectiveness of Vegetative Filter Strips in Controlling Losses of Surface-applied Poultry Litter Constituents. Transactions of the American Society of Agricultural Engineers 38(6):1687-1692. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/poultry.html

> Vegetative filter strips (VFS) have been shown to have high potential for reducing nonpoint source pollution from cultivated agricultural source areas, but information from uncultivated source areas amended with poultry litter is limited. Simulated rainfall was used in analyzing effects of VFS length on quality of runoff from fescue plots amended with poultry litter. The VFS reduced mass transport of ammonia-nitrogen, total Kjeldahl nitrogen, ortho-phosphorus, total phosphorus, chemical oxygen demand, and total suspended solids. Effectiveness of VFS in terms of mass transport reduction was unchanged, however, beyond 3.1 m length for TSS and COD and averaged 35 and 51%, respectively. The VFS were ineffective in removing nitrate-nitrogen from the incoming runoff. Removal of litter constituents was described very well by a first-order relationship between constituent removal and VFS length.

Cheng, J., J. Pace, K.D. Zering, J.C. Barker, K.F. Roos, and L.M. Saele. (1999) Evaluation of Alternative Swine Waste Treatment Systems in Comparison with Traditional Lagoon System. Paper to be presented at Livestock Waste Management Symposium, American Society of Agricultural Engineers, Des Moines, Iowa, October 2000.

Chescheir, G.M., R. W. Skaggs, and J. W. Gilliam. (1992) Evaluation of Wetland Buffer Areas for Treatment of Pumped Agricultural Drainage Water. Transactions of the American Society of Agricultural Engineers 35(1):175-182.

CH_2M Hill and Payne Engineering. (1997) Constructed Wetlands for Animal Waste Treatment: A Manual on Performance, Design, and Operations with Case Studies. Prepared for U.S. Environmental Protection Agency's Gulf of Mexico Program.

Clausen, J.C. and D.W. Meals, Jr. (1989). Water Quality Achievable with Agricultural Best Management Practices. Journal of Soil and Water Conservation 44(6):593-596. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> Water quality in runoff from agricultural areas under best management was compared with water quality standards, where appropriate, and with other measures of treated water, thereby defining the water quality achievable by using best management practices. The study draws upon results obtained from 7 years of water quality monitoring in the LaPlatte River and St. Albans Bay watersheds in Vermont of BMPs implemented for

manure management, barnyard runoff, and milkhouse wastes. These studies include long-term stream monitoring for sediment and nutrient concentration and load, as well as intensive evaluation of the treatment effectiveness of certain BMPs, such as vegetated filter strips and manure storage, on concentration and export of sediment, nutrients, and bacteria. Results indicate that BMPs may be highly effective in reducing pollutant concentrations and loads, but runoff may continue to exceed water quality criteria.

Clawson, J.E., J.C. Buckhouse, J.R. Miner, and J.A. Moore. (1994) An Evaluation of Off-site Water Development and Fence Configurations Designed to Ameliorate Water Quality Impacts by Livestock. Oregon State University, Oregon Academy of Science.

Cooper, C. M., S.I. Testa, and S.S. Knight. (1994) Preliminary Effectiveness of Constructed Wetlands for Dairy Waste Treatment. Environmentally Sound Agriculture Proceedings of the Second Conference, April 20-22, 1994, pp. 439-446.

Cooperband, L. (1997) Managing Dairy Waste Using Commercial Constructed Wetlands and Composting. Research Projects, Northeast Region. Project Number: LNE95-62: Sustainable Agriculture Research and Education. 22 pp.

Coyne, M.S., R.A. Gilfillen, R.W. Rhodes, and R.L. Blevins. (1995) Soil and Fecal Coliform Trapping by Grass Filter Strips During Simulated Rain. Journal of Soil and Water Conservation 50:405-408.

Coyne, M.S., R.A. Gilfillen, A. Villalba, R.W. Rhodes, L. Dunn, R.L. Blevins and Z. Zhang. (1998) Fecal Bacteria Trapping by Grass Filter Strips During Simulated Rain. Journal of Soil and Water Conservation 53(2):140-145.

Cronk, J.K., V. Vodmur, and A. Shirmohammadi. (1994) An Evaluation of Wetlands for the Treatment of Dairy Effluent: Results from the First Year of Operation. Written presentation for American Society of Agricultural Engineers, Paper No. 94-2600. December 13-16, 1994, Atlanta, Georgia.

Cronk, J.K. (1996) Constructed Wetlands to Treat Wastewater From Dairy and Swine Operations: A Review. Agricultural Ecosystems and Environment 58(2/3):97-114.

Dalsted, N.L., R.M. Waskom, and D.G. Westfall. (1997) Validating Alternative Manure Management Systems for Dairy and Beef Confined Feeding Operations. Report to American Farm Bureau, Department of Soil and Crop Sciences. Colorado State University, Fort Collins, Colorado.

Davis, L., M. Brittingham, L. Garber, and D. Rourke. (1991) Stream Bank Fencing. Extension Circular 397, Penn State College of Agricultural Science, University Park, Pennsylvania.

DeLuca, T.H. and D.K. DeLuca. (1997) Composting for Feedlot Manure Management and Soil Quality. Journal of Production Agriculture, American Society of Agronomy 10(2):236-241. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/beef.html

> In this paper we view cooperative on-farm composting as the combination and processing of feedlot manure with crop stover to produce a beneficial natural soil amendment and fertilizer for those fields from which the stover was taken. Cooperative on-farm composting would help protect surface and groundwater from nutrient loading, save resources, and help renew social ties within the agricultural community. Composting stabilizes nutrients, kills pathogens and weed seeds, reduces moisture content, reduces odor, and improves physical properties of manure, thereby improving its value as a soil amendment and fertilizer. Although some N in raw manure is lost during composting, the end product differs from raw manure in that it exhibits minimal N loss in storage or after field application. Composted manure can become the primary fertilizer for grain production once the cumulative N mineralization from previous applications reach steady-state. The use of composted manure improves soil quality and greatly reduces total energy consumption compared with the use of commercial fertilizer.

Dillaha, T.A. (1986) Use of Vegetative Filter Strips to Minimize Sediment and Phosphorus Losses from Feedlots. Phase 1. Experimental Plot Studies. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Financed in part by U.S. Department of Interior, as authorized by the Water Resources Research Act of 1984. Project S-010, pp. 67-68.

Dillaha, T.A., J.H. Sherrard, D. Lee, S. Mostaghimi, and V.O. Shanholtz. (1988) Evaluation of Vegetative Filter Strips as Best Management Practices for Feed Lots. Journal of Water Pollution Control Federation 60(7):1231-1238.

Dou, Z., R.A. Kohn, J.D. Ferguson, R.C. Boston, and J.D. Newbold. (1996) Managing Nitrogen on Dairy Farms: An Integrated Approach. I. Model Description. Journal of Dairy Science, American Dairy Science Association 79(11):2071-2080. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/dairy2.html

> Nitrogen management on dairy farms can be enhanced with integrated and quantified information about N flow through various components of the system. A computer worksheet was developed to integrate several aspects of farm management, including ration formulation, crop selection, and manure application. The availability of manure N and the field history of soil and crop management assisted in the determination of crop N fertilization. Manipulating dietary formulations to meet herd nutritional requirements with less dietary N can be helpful to optimize feed selection and reduce manure N excretion simultaneously. Aggregated annual feed requirements of the herd foster the development of cropping and feeding strategies. The worksheet largely was empirically

based, simple to use, and adaptable to any size dairy farm. The model was used to compare efficiencies of N utilization and balances of inputs and outputs with different management strategies and was demonstrated to be a useful planning tool for N management to minimize potential N losses to the environment.

Doyle, R.C. and G.S. Stanton. (1977) Effectiveness of Forest and Grass Buffer Strips in Improving the Water Quality of Manure Polluted Runoff. American Society of Agricultural Engineers, Paper No. 77-2501. St. Joseph, Michigan.

DuBowy, P.J. and R.P. Reaves (Editors). (1994) Constructed Wetlands for Animal Waste Management, 1994 - Conference Proceedings. Papers from the Constructed Wetlands for Animal Waste Management Workshop. Lafayette, Indiana. April 4-6, 1994, 188 pp.

Dunlap, T.F., R.A. Kohn, and K.F. Kalscheur. (1997) Effect of Animal Groupings Strategies on Nutrient Losses From the Dairy Farm. Journal of Dairy Science 80(1):246.

Edens, F. and C. Simons. (1998) Use of Phytase in Poultry Diets to Reduce Phosphorus Excretion. North Carolina State University, Department of Poultry Science, and Center for Applied Poultry Research, Netherlands.

Edwards, D.R. and T.C. Daniel. (1993) Drying Interval Effects on Runoff from Fescue Plots Receiving Swine Manure. Transactions of the American Society of Agricultural Engineers 36:1673-1678. Abstract retrieved January 18, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9605.html

This experiment was conducted to assess the influences of swine manure treatment and drying interval between manure application and first runoff event on quality of runoff from fescue plots. Runoff was generated from simulated rainfall and sampled at 0.08 h intervals during runoff. Runoff concentrations of all manure constituents investigated were higher for the manure-treated plots than for the untreated plots. Runoff increased with drying interval due to nitrification, but concentrations of other manure constituents were unaffected by drying interval. Amounts of constituents lost from the plots in runoff were higher for the manure-treated plots than for the untreated plots, but all losses were found independent of drying interval. Analyses of the noncomposited runoff samples revealed high variability in the response of runoff quality to time after the beginning of runoff for all parameters investigated. Data from the non-composited samples did not lend itself to generalized descriptions of changes with respect to time of runoff concentrations of manure constituents.

Edwards, D.R., T.C. Daniel, and P.A. Moore, Jr. (1996) Vegetative Filter Strip Design for Grassed Areas Treated with Animal Manures. Applied Engineering in Agriculture 12(1):31-38.

Edwards, D.R., P.A. Moore, Jr., T.C. Daniel, P. Srivastava, and D.J. Nichols. (1997) Vegetative Filter Strip Removal of Metals in Runoff from Poultry Litter-amended Fescuegrass Plots. Transactions of the American Society of Agricultural Engineers 40(1):121-127. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/poultry.html

> Runoff from land areas amended with poultry manure can contain elevated concentrations of metals such as Cu, Fe, and Zn. This experiment assessed the impact of vegetated filter strip (VFS) length on concentrations and mass losses of Cu, Fe, K, Na, Ni, and Zn in runoff from fescuegrass plots treated with poultry litter. The runoff was produced from simulated rainfall. Runoff Ni concentrations were below detection levels in all cases. Concentrations of Cu, Fe, K, Na, and Zn did not differ between litter-treated plot lengths but were significantly affected by VFS length, decreasing in an approximately first order fashion. Means separation indicated that concentrations of Cu, Fe, K, and Zn did not significantly decrease after a VFS length of 3 m, while Na concentrations decreased up to a VFS length of 6 m. Mass transport of only Cu significantly decreased with increasing VFS, suggesting that VFS removal mechanisms such as adsorption to clay particles might play a larger role with regard to Cu than to Fe, K, Na, and Zn.

Edwards, W.M., L.B. Owens, R.K. White, and N.R. Fausey. (1986) Managing Feedlot Runoff with a Settling Basin Plus Tiled Infiltration Bed. Transactions of the American Society of Agricultural Engineers 29(1):243-247.

Eghball, B. and J.F. Power. (1994) Beef Cattle Feedlot Manure Management. Journal of Soil and Water Conservation 49(2):113-122.

Fajardo, J., J.W. Bauder, and S.D. Cash. (In Press) Managing Nitrate and Bacteria in Runoff from Livestock Confinement Areas with Vegetative Filter Strips. Journal of Soil and Water Conservation. Retrieved January 7, 2002 from the World Wide Web: http://landresources.montana.edu/Faculty/Bauder.htm

Fausey, N.R., W.M. Edwards, L.B. Owens, and R.K. White. (1988) Subsurface Drained Infiltration Beds for Feedlots Runoff Management. Transactions of the American Society of Agricultural Engineers 31(1):98-101. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> Sloping infiltration areas with enclosing dikes and subsurface drains were evaluated for their effectiveness in removing pollutants from the runoff water from a small paved feedlot. Two designs of this forced infiltration system concept were tested simultaneously. The results were compared to the quantity and quality of discharge from sodded filter strips tested previously. Volume of discharge, chemical oxygen demand, total solids, ammonium nitrogen, total nitrogen, nitrate nitrogen, organic nitrogen, soluble phosphorus, total phosphorus and potassium were determined for the tile outflow from

various sampling points within each system. The system with a single subsurface drain parallel to the surface slope discharged less of all pollutants than two consecutive 30 m long sodded filter strips. The other system with a series of cross slope subsurface drains and surface dikes discharged about the same amount of pollutant as the first of two consecutive 30 m long filter strips but more than the second filter strip.

Fleming, R.A. and B.A. Babcock. (1997) Resource or Waste? The Economics of Swine Manure Storage and Management. Working Paper 97-WP178. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa, 20 pp.

Gao, Y.C., P.H. Liao, and K.V. Lo. (1993) Chemical Treatment of Swine Wastewater. Journal of Environmental Science Health. Part A. Environmental Science Engineers A28:795-807.

Gburek, W.J. and H.B. Pionke. (1995) Management Strategies for Land-based Disposal of Animal Wastes: Hydrologic Implications. *In:* Animal Water and the Land-water Interface, K. Steele (Editor). Lewis Publishers, CRC Press, Boca Raton, Florida, pp. 313-323.

Hafner, C.L. and M.C. Brittingham. (1993) Evaluation of a Stream-bank Fencing Program in Pennsylvania. Wildlife Society Bulletin 21(3):301-315.

Hammer, D.A. (Editor). (1989) Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural. Lewis Publishers, Chelsea, Michigan.

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Hawkins, G.L., D.T. Hill, E.W. Rochester, and C.W. Wood. (1998) Evaluation of Vegetative Filter Strips for Swine Lagoon Wastewater. Transactions of American Society of Agricultural Engineers 41(3):639-643.

Heatwole, C.D., P.L. Diebel, and J.M. Halstead. (1990) Management and Policy Effects on Potential Groundwater Contamination From Dairy Wastes. Water Resource Bulletin 26(1):25-34. Abstract retrieved January 4, 2002 from the World Wide Web:http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.145104.3747.html

A combined economic and water quality modeling framework was used to evaluate impacts of alternative policies and management practices on reducing nitrate movement to groundwater for dairy farms in Rockingham County, Virginia. The analysis considers three on-farm manure storage options, cost-sharing programs for purchasing manure storage facilities, restrictions on nitrogen application rates, and a tax on commercial fertilizer. The CREAMS model was used to estimate nitrate leaching from the crop root zone for various nutrient (and manure) management practices, based on timing and rate of manure and fertilizer applications.

Hill, D.T., J.W. Rogers, V.W.E. Payne, and S.R. Kown. (1996) Evaluation of Free-Water-Surface Constructed Wetlands for the Treatment of Poultry Lagoon Effluent. Transactions of American Society of Agricultural Engineers 39(6):2113-2117. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/conwet2.html

A free-water-surface constructed wetlands system was installed at the Auburn University poultry unit in Auburn, Alabama. The wetlands system, consisting of three series of dual cell wetlands, was installed for the purpose of treating effluent from an anaerobic poultry waste lagoon. Samples were collected from the influent and effluent of the system during the period from August 1993 until March 1994 in order to evaluate the ability of constructed wetlands to treat poultry lagoon wastewater and the effects cold winter months have on the treatment process. To investigate and monitor groundwater impact, two lysimeters were installed in each cell of each series at depths of 0.6 m and 1.3 m.

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Groundwater studies conducted in north Florida indicate that improperly managed waste from dairy farms can create groundwater nitrate pollution. A study was conducted using suction lysimeters and the CREAMS computer model to evaluate recommended best management practices (BMPs) at several dairy farms in north Florida. The BMPs were determined from a nitrogen balance to reduce the amount of nitrate leaching from the dairies while maintaining economic vitality. A complete list of BMPs is given within the article.

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Hubbard, R.K., G. Vellidis, R. Lowrance, J.G. Davis, and G.L. Newton. (1995) Using Riparian Buffers to Treat Animal Waste. *In*: Animal Waste and the Land-water Interface. Lewis Publishers, Boca Raton, Florida, pp. 127-134.

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Humenik, F., J. Zublena, and J. Barker. (1993) Constructed Wetlands for Animal Wastewater Treatment. *In*: Subseries: Water Quality & Waste Management. North Carolina Agricultural Extension Service, Raleigh, North Carolina. 473-13, 3 pp.

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Kasi, V. and B. Botter. (1994) Streambank Fencing for the Remediation of Agricultural Nonpoint Source Pollution. *In*: Riparian Ecosystems in the Humid U.S.: Functions, Values, and

Management. Proceedings of a conference March 15-18, 1993, Atlanta, Georgia. National Association of Conservation Districts, Washington, DC, pp. 301-305.

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Knight, R.L. (1992) Ancillary Benefits and Potential Problems with the Use of Wetlands for Nonpoint Source Pollution Control. Ecological Engineering 1:97-113.

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Lanyon, L.E. (1994) Dairy Manure and Plant Nutrient Management Issues Affecting Water Quality and the Dairy Industry. Journal of Dairy Science 77:1999-2007. Abstract retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

> A formal management process can guide decisions about existing crop nutrient utilization potential, provide a framework for tracking nutrients supplied to crops, and identify future requirements for dairy manure management to protect water quality. Farm managers can use the process to plan daily activities, to assess annual nutrient management performance, and to chart future requirements as herd size increases. Agronomic measures of nutrient balance and tracking of inputs and outputs for various farm management units can provide the quantitative basis for management to allocate better manure to fields, to modify dairy rations, or to develop alternatives to on- farm manure application. Involving the dairy industry and off-farm stakeholders as participants in the management process for field, farm, and regional dairy production can be the basis for decision-making to reconcile the sometimes conflicting demands of production and water quality protection.

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Lesoing, G., T. Klopfenstein, and D. Duncan. (1996) Composting – a Feedlot Waste Management Alternative. Agricultural Research Division, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln. 66-A, pp. 77-79.

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Liao, P.H., A.T. Vizcarra, A. Chen, and K.V. Lo. (1993) Composting of Separated Solid Swine Manure. Journal of Environmental Science Health. Part A. Environmental Science Engineers 28(9):1889-1901.

Liu, F., C.C. Mitchell, D.T. Hill, J.W. Odom, and E.W. Rochester. (1997) Phosphorus Recovery in Surface Runoff from Swine Lagoon Effluent by Overland Flow. Journal of Environmental Quality 26(4):995-1001. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> A study was conducted in Alabama to determine phosphorus removal by overland flow of swine lagoon effluent on bermudagrass and annual ryegrass.

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Miller, M.H., J.B. Robinson, and R.W. Gillham. (1985) Self-Sealing of Earthen Liquid Manure Storage Ponds. I: A Case Study. Journal of Environmental Quality 14(4):533-538. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> A monitoring system was established on an unlined, earthen storage pond near Kitchener, ON prior to the addition of liquid manure from a 4500-head beef feeding operation. The bottom of the pond, which had a surface area when full of 2 ha, was a coarse textured sand. This material, with some gravel layers, extended below the water table, which was initially at 13.7 m below the ground surface. A platform, at which soil moisture measurement and groundwater sampling tubes were installed, was constructed within the pond. Additional groundwater sampling tubes were installed at several points surrounding the pond. Moisture content of the soil immediately below the pond reached saturation when liquid manure was first added but began to decrease within 2 weeks and reached a steady state at a water potential within 90 days. The infiltration rate at this time was estimated to be a value considered to indicate that the bottom was effectively sealed. There was a rapid increase in Cl content of the groundwater within 2 weeks of manure addition but the concentration declined to initial values within 12 weeks. There was no evidence of elevated Cl concentrations in groundwater outside the boundaries of the pond.

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Niebling, H. and D. Falk. (1997) Design and Construction of Earthen Embankment for Animal Liquid-Waste Containment. University of Idaho, College of Agriculture, Cooperative Extension System, Agricultural Experiment Station. 8 pp.

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Rice, J.M., A.A. Szogi, S.W. Broome, F.J. Humenik, and P.G. Hunt. (1998) Constructed Wetland Systems for Swine Wastewater Treatment: Animal Production Systems and the Environment. *In*: Proceedings of an International Conference on Odor, Water Quality, Nutrient Management, and Socio-economic Issues, Iowa State University.

Richard, T.L. (1998) Composting Strategies for High Moisture Manures. Manure Management in Harmony with the Environment and Society Conference. The Soil and Water Conservation Society, West North Central Region. February 10-12, 1998, Ames, Iowa, pp. 135-138.

Roberts, R.J. and C.J. Clanton. (1992) Plugging Effects from Livestock Waste Application on Infiltration and Runoff. Transactions of the American Society of Agricultural Engineers 35:515-522. Abstract retrieved January 18, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9605.html

> A rainfall simulator was used on repacked Waukegan silt loam and Hubbard loamy sand soil columns to determine the combined effect of rainfall and livestock waste application on infiltration and runoff. Dairy and swine waste slurries were either surface-applied or incorporated. Livestock waste application noticeably reduced the amount of runoff during a series of artificial rainfall events for all cases with the exception of swine waste incorporated into the silt loam soil. Loamy sand exhibited short-term plugging when both wastes were surface-applied with no incorporation. Surface-application of dairy waste on the silt loam soil apparently prevented formation of a surface seal and improved the infiltration capacity. of the soil. Less surface-scaling in waste-applied columns may be attributed to increased organic matter on the surface of the soil that aided aggregate stability.

Robillard, P.D. and M.F. Walter. (1986) The Utilization of Tillage as a Phosphorus Control Practice for Manure Spread Fields. American Society of Agricultural Engineers, Paper No. 86-206. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> Experimental results from rainfall simulator on manure applications. Application rates were 22-135 MT/ha with different incorporation depths. Incorporation was preferred to surface application.

Rowsell, J.G., M.H. Miller, and P.H. Groeneuett. (1985) Self-Sealing of Earthen Liquid Manure Storage Ponds: II. Rate and Mechanism of Sealing. Journal of Environmental Quality 14(4):539-543. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.125701.3594.html

> A laboratory study with soil columns to measure rate of sealing under liquid beef manure at 50 g/kg. Sealing occurred in 10 days on clay soil but required more than 30 days on sandy loam and loam.

Rynk, R. (1987) On Farm Composting: The Opportunities, Benefits, and Drawbacks. Engineering Notes, University of Massachusetts.

Safley, L.M., Jr. and P.W. Westerman. (1992) Performance of a Low Temperature Lagoon Digester. Bioresource Technology 41:167-175.

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Safley, L.M. Jr., C.D. Fulhage, R.L. Huhnke, and D.D. Jones. (1994) Lagoon Management. Extension Technical Bulletin, University of Arkansas Cooperative Extension Service. E-1341, 8 pp.

Sanderson, M.A., R.M. Jones, M.J. McFarland, J. Stroup, R.L. Reed, and J.P. Muir. (2001) Nutrient Movement and Removal in Switchgrass Biomass-Filter Strip System Treated with Dairy Manure. Journal of Environmental Quality 30:210-216.

Schellinger, G.R. and J.C. Clausen. (1992) Vegetative Filter Treatment of Dairy Barnyard Runoff in Cold Regions. American Society of Agronomy, Journal of Environmental Quality 21(1):40-45. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9502.html

> A vegetative filter strip was installed to treat barnyard runoff from an active dairy farm in Vermont. Runoff from a concrete surfaced barnyard flowed through a detention pond, then onto a vegetative filter strip. It was concluded that poor filter strip performance was

due to an excessive hydraulic loading rate resulting in an inadequate detention time for proper treatment. A preferential flow path from the level lip spreader to the subsurface drain tiles may have contributed to the poor subsurface treatment performance.

Schmidt, J.L. and B.F. Wolfley. (1992) Protecting Groundwater: Managing Livestock on Small Acreage. Extension Bulletin, Washington State University Cooperative Extension Service Pullman, Washington. 1713, 6 pp.

Schneider, J.H. (1990) Advantages of Multi-cell Animal Waste Lagoons. American Society of Agricultural Engineers. Paper No. 90-4521, 12 pp. Presented at the "1990 International Winter Meeting sponsored by The American Society of Agricultural Engineers," December 18-21, 1990, Chicago, Illinois.

Schwer, C.B. and J.C. Clausen. (1989) Vegetative Filter Treatment of Dairy Milkhouse Wastewater. Journal of Environmental Quality 18:446-451. Abstract retrieved January 10, 2002 from the World Wide Web:
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A vegetated filter strip constructed to treat milkhouse wastewater from a Vermont dairy farm was evaluated to determine its effectiveness in reducing solids, P and N concentrations and exports in surface and subsurface flow. Retention was the greatest during the growing season and the poorest during snowmelt periods. Concentrations in subsurface outputs were greater than in surface runoff and over 75% of the mass export was in subsurface flow. Comparisons of this study with values reported in the literature suggests that hydraulic loading rate governs the effectiveness of filter strip treatment.

Sheffield, R.E., S. Mostaghimi, D.H. Vaughan, E.R. Collins, Jr., and V.G. Allen. (1997) Off-Stream Water Sources for Grazing Cattle as a Stream Bank Stabilization and Water Quality BMP. Transactions of the American Society of Agricultural Engineers 40(3):595-604.

Shreve, B.R., P.A. Moore, Jr., T.C. Daniel, D.R. Edwards, and D.M. Miller. (1996) Best Management Practices to Limit Nonpoint Source Pollution from Pastures. Proceedings of the South Pasture Forage Crop Improvement Conference, New Orleans, Louisiana. Agricultural Research Service (Southern Region), U.S. Department of Agriculture. pp. 81-87.

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Sievers, D.M. (1997) Performance of Four Constructed Wetlands Treating Anaerobic Swine Lagoon Effluents. Transactions of the American Society of Agricultural Engineers 40(3):769-

775. Abstract retrieved January 14, 2002 from the World Wide Web:
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Effluents from both cells of a two-cell anaerobic lagoon system beating flushed swine waste were loaded into two types of constructed wetlands, submerged flow and free water surface. The wetlands were planted to Bulrush, Soft Rush, and Arrowhead. Effluents from the lagoons were too concentrated to achieve wetland effluent criteria suggested by the NRCS. This study showed that the Rational Method for sizing constructed wetlands to treat anaerobic swine lagoon wastewaters to achieve a wetland effluent criteria <30 mg/L BOD5 was inadequate. Continuous reduced environmental conditions in the wetlands was the primary reason for this, but high ammonia and TKN loadings also contributed.

Sohail, S. and D. Roland. (1999) Phytase Enzyme Proving Helpful to Poultry Producers and Environment. Highlight of Agricultural Research, Alabama Agricultural Experiment Station, 46(1). Abstract retrieved January 21, 2002 from the World Wide Web:
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Results of a study that found the use of phytase in poultry diets will significantly reduce environmental phosphorus pollution.

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This study assessed the effects of pollutant source area (fescue pasture treated with poultry litter), length and VFS (fescue pasture), length on VFS removal of nitrate N (NO3-N), ammonia N (NH3-N), total Kjeldahl N (TKN), ortho-P (PO4-P), total P (TP), total organic carbon (TOC), total suspended solids (TSS), and fecal coliform (FC) from incoming runoff. This research examined poultry litter-treated lengths of 6.1, 12.2, and 18.3 m, with corresponding VFS lengths of up to 18.3 m, 12.2 m, and 6.1 m, respectively. Runoff was produced from simulated rainfall applied to both the litter-treated and VFS areas at 50 mm/h for 1 h of runoff. Pollutant concentrations in runoff were unaffected by litter-treated length but demonstrated a first-order exponential decline with increasing VFS length except for TSS and FC. Runoff mass transport of NH3-N, TKN, PO4-P, TP and TOC increased with increasing litter-treated length (due to increased runoff) and decreased (approximately first-order exponential decline) with increasing VFS length when affected by VFS length. Effectiveness of the VFS in terms of NH3-N, TKN, PO4-P, TP and TOC removal from runoff ranged from 12-75, 22-67, 22-82, 21-66, and 8-30% respectively. The data from this study can help in developing and testing models that simulate VFS performance and thus aid in the design of VFS installed downslope of pasture areas treated with animal manure.

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Sugiharto, T., T.H. McIntosh, R.C. Unrig, and J.J. Lavdinois. (1994) Modeling Alternatives to Reduce Dairy Farm and Watershed Nonpoint Source Pollution. Journal of Environmental Quality 23:18-24.

Sutton, A.L., J.R. Malayer, M.A. Diekman, D.T. Kelly, D.D. Jones, and G.G. Long. (1987) Effects of Manure Management and Building Environments on Swine Health and Productivity. Transactions of the American Society of Agricultural Engineers 30(6):1764-1771. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9366.html

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Field research was conducted at commercial dairy farms in Erath County, Texas, to develop improved design criteria for storage, treatment, and land application systems for open lot dairies. Water use and waste water from milking parlors were monitored along with rainfall runoff from open lots. Two-stage anaerobic lagoon systems achieved higher solids and nutrient removal efficiencies than a combination of settling basin and one-stage anaerobic lagoons.

Tanner, C.C., J.P.S. Sukias, and M.P. Upsdell. (1988) Relationship Between Loading Rates and Pollutant Removal During Maturation of Gravel-bed Constructed Wetlands. Journal of Environmental Quality 27:448-458.

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Association on Water Pollution Research and Control. *In*: Series Analytic: Wetlands Systems in Water Pollution Control, H.J. Bavor and D.S. Mitchell (Editors). Australia. 29:85-93.

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Tiedemann, A.R. and D.A. Higgins. (1989) Effects of Management Strategies on Water Resources. *In*: Managing Interior Northwest Rangelands: the Oregon Range Evaluation Project, T.M. Quigley, H.R. Sanderson, and A.R. Tiedemann (Editors). General Technical Report. Research Paper PNW-238. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, pp. 57-91.

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Fertilizer Application

Recent Research

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Baker, J.L., W.G. Krumpton, R.S. Kanwar, S.K. Mickelson, and U.S. Tim. (1995) Mitigation Practices to Reduce Agricultural Chemical Transport to Water Resources. *In*: Proceedings of the Annual Underground Injection Control and Ground Water Protection Forum, Kansas City, Missouri, October 8-11, 1995. Ground Water Protection Council, Oklahoma City, Oklahoma.

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> ANSWERS-2000, a non-point-source planning model was modified to simulate long-term nitrogen (N) and phosphorus (P) transport from rural watersheds. The model simulates infiltration, evapotranspiration, percolation, and runoff and losses of nitrate, adsorbed and dissolved ammonium, adsorbed total Kjeldahl N, and adsorbed and dissolved P losses. Eight soil nutrient pools are modeled: stable organic N, active organic N, nitrate, ammonium, and stable mineral P, active mineral P, organic P, and exchangeable P. The model was validated on two small watersheds without calibration and on a large watershed with calibration of only the sediment detachment parameters. Predicted cumulative runoff, sediment, nitrate, dissolved ammonium, adsorbed total Kjeldahl N, and orthophosphorus P losses were within a factor of 2 of observed values (-40 to +44% of observed values). Predictions of individual runoff event losses were not as accurate (-98 to +250%). The model seriously underpredicted adsorbed ammonium losses by up to 97%, and additional work is recommended on this submodel. In a practical application, the use of the model in evaluating the cost-effectiveness of alternative management scenarios was demonstrated.

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> The effectiveness of vegetative filter strips (VFS) in removing sediment and nutrients from cropland runoff is discussed. VFS as presently implemented were found to be relatively ineffective for sediment and nutrient removal. Recent state and federal policies affecting VFS implementation are discussed and recommendations are made for future research to improve VFS design procedures and effectiveness.

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Franzluebbers, A.J., R.L. Haney, and F.M. Hons. (1995) Soil Nitrogen Mineralization Potential for Improved Nitrogen Fertilizer Recommendations and Decreased Nitrate Contamination of Ground Water. Technical Report No. 171. Texas Water Resources Institute and The Texas A & M University System. College Station, Texas. Retrieved January 7, 2002 from the World Wide Web: http://twri.tamu.edu/reports/1995/171/

> In order to prevent overfertilization, which could lead to groundwater contamination, rapid and accurate soil testing procedures are needed to evaluate agricultural surface soils for their potential to mineralize C and N. Our objectives were to determine optimum conditions for estimating soil microbial biomass (SMB) from previously dried soils and to identify a quick, reliable biochemical predictor of soil N mineralization potential.

Gilliam, J.W., J.E. Parsons, and R.L. Mikkelsen. (1997) Nitrogen Dynamics and Buffer Zones. *In*: Buffer Zones: Their Processes and Potential and Water Protection, N.E. Haycock, T.P. Burt, K.W.T. Goulding, and G. Piney (Editors.) Quest Environmental, Harpenden Herts. U.K. pp. 54-61.

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Gordon, W.B. (1998) Effects of Placement, Rate, and Source of Starter Fertilizer Containing Potassium On Corn and Soybean Production. *In*: Kansas Fertilizer Research: Report of Progress 829. Kansas State University Agricultural Experiment Station and Cooperative Extension Service. pp. 69-72. Retrieved January 7, 2002 from the World Wide Web: http://www.oznet.ksu.edu/library/crpsl2/SRP829.pdf

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> Denitrification was measured in two grass and two forest vegetated filter strips (VFS) in Rhode Island. The grass plots were established on a well-drained soil and were planted to either tall fescue or reed canarygrass. Nitrate and NO3 plus-C amended rates were consistently higher in the grass plots than in the forest plots. Nitrate-plus carbon-amended rates were higher than NO3-amended rates in all plots, but the differences were significant in the forest plots only. The results suggest that the ability of VFS to support denitrification varies strongly with vegetation, soil type and pH, and that denitrification in VFS may be amenable to management.

Gupta, R.K., R.P. Rudra, W.T. Dickinson, and G.J. Wall. (1997) Surface Water Quality Impacts of Tillage Practices Under Liquid Swine Manure Application. Journal of the American Water Resources Association 33(3):681-687. Retrieved January 7, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.134024.4901.html

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Hamlett, J.M. and D.J. Epp. (1994) Water Quality Impacts of Conservation and Nutrient Management Practices in Pennsylvania. Journal of Soil and Water Conservation 49(1):59-66. Abstract retrieved January 7, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.140355.4945.html

> A field-scale microcomputer model, CREAMS, was used to assess the impacts of selected best management practices (BMPs) and nutrient management programs (NMPs) on sediment and nutrient losses from three locations with three soil and field configurations common to the Chesapeake Bay drainage area in Pennsylvania. The baseline NMP followed traditional manure and fertilizer application practices and the improved NMP used an improved, high management system that incorporated best timing, placement, and types of nutrient additions. BMPs increased percolation and decreased runoff compared to moldboard plowing with no conservation practices. Although BMPs reduced sediment-associated N and P losses, the improved NMPs, as compared with the traditional baseline NMP, had little effect on these losses. BMPs

tended to increase, whereas the improved NMPs substantially reduced, nitrate leaching. The improved NMPs also greatly reduced P losses from those sites where P loss was predominantly in soluble form rather than sediment associated. The use of BMPs and improved NMPs together effectively reduced sediment and total nutrient losses.

Hatfield, J. and D. Jaynes. (2000?) Walnut Creek Nitrogen Initiative. Retrieved January 4, 2002 from the World Wide Web:
http://nps.ars.usda.gov/projects/projects.htm?accession=400798

Project was completed December 2000, but it is uncertain if the final results have been published at this time. Premise of the project was to determine the effect on surface and ground water quality near Walnut Creek through the use of BMPs for nitrogen use. The project also sought to identify the sociological and economic barriers towards the adoption of BMPs for nitrogen use by cooperating producers.

Huang, W. and R.M. Lantin. (1993) A Comparison of Farmers' Compliance Costs to Reduce Excess Nitrogen Fertilizer Use Under Alternative Policy Options. Rev. Agric. Econ. 15(1):51-62. Abstract retrieved January 7, 2002 from the World Wide Web:
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Farmers' compliance associated with using different crop rotation patterns under alternative farm policy options are estimated. The policy options considered include the Current Farm Program, a No Farm Program Option, a Nitrogen Fertilizer Tax Option, a Corn Sales Tax Option, and a Limiting Nitrogen Fertilizer Use Option. To achieve an objective of zero excess nitrogen fertilizer available for potential leaching into groundwater, crop rotation patterns associated with the Limiting Nitrogen Fertilizer Use Option have the lowest cost to the farmer. If some excess nitrogen is allowed, crop rotation compliance under the Farm Program has the lowest cost.

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A nitrogen balance model is used to investigate the adoption of a crop rotation and the limitation on the application of nitrogen fertilizer to reduce excess nitrogen.

Huang, W.Y., T.I. Hewitt, and P. Shank. (1998) An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses. J. Agric. Retour. Econ. 23(2):445-467.

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The advantages of using insurance to help a farmer adopt a best nitrogen management plan (BNMP) that reduces the impact of agricultural production on the environment is analytically and empirically demonstrated. Using an expected value analysis, it is shown that an insurance program can be structured so as to reduce a farmer's cost of bearing the adoption risk associated with changing production practices and, thus, to improve the farmer's certainty equivalent net return thereby promoting the adoption of a BNMP. Using the adoption of growing-season only N fertilizer application in Iowa as a case study, it is illustrated how insurance may be used to promote the adoption of this practice to reduce N fertilizer use. It is shown that it is possible for a farmer and an insurance company both to have an incentive to develop an insurance adoption program that will benefit both the farmer and the insurance company, increasing net social welfare and improving environmental quality in Iowa.

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Four sets of eight or twelve 0.7 ha plots, designed for soil and hydraulic uniformity, were used to screen potential BMPs for reducing total phosphorus (TP) concentrations and loadings in the Everglades Agricultural Area (EAA) of south Florida. The study showed that there were no differences in P concentrations in drainage water between sugarcane and drained fallow fields. Slow drained sugarcane plots exhibited significantly higher TP concentrations than the fast drained plots. However, TP loads were significantly higher for fast drained plots than for the slow drained plots. Rice as a P filter crop following radishes reduced TP concentrations and loadings. Finally, banding P fertilizer at a reduced rate for cabbage reduced TP concentrations compared to those for broadcasted P at the full recommended level. All treatment TP loadings leaving the plots in drainage water were close in magnitude to TP loadings to the plots, even under heavy fertilization. This indicates that the EAA system is currently a net assimilator of P.

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Extension Service. pp. 80-84. Retrieved January 7, 2002 from the World Wide Web: http://www.oznet.ksu.edu/library/crpsl2/SRP829.pdf

Janssen, K.A. and G.M. Pierzynski. (2001) Integrated Agricultural Management Systems to Improve The Quality of Kansas Surface Waters. *In*: Kansas Fertilizer Research 2001: Report of Progress 885. Kansas State University Agricultural Experiment Station and Cooperative Extension Service. pp. 55-59. Retrieved January 7, 2002 from the World Wide Web: http://www.oznet.ksu.edu/library/crpsl2/srp885.pdf

Kanwar, R.S., J.L. Baker, and S.W. Melvin. (1986) Alternatives to the Use of Agricultural Drainage Wells. Water Resources Bulletin 22(4):573-580.

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> A field study utilizing simulated rainfall and bare plots conducted to study the effectiveness of vegetated filter strips in removing nutrients and sediments from agricultural runoff. Losses of N and P from plots with filters were highly variable as compared to losses from plots with no filters. Generally, nutrient removals appeared to be greater with the longer filters, but decreased as the number of runoff events increased.

McCarthy, M. and R. Dodd. (1995) Cost-Effectiveness and Targeting of Agricultural BMPs for the Tar-Pamlico Nutrient Trading Program. Paper presented at Watershed '96 Proceedings. http://www.epa.gov/owowwtr1/watershed/Proceed/mccarthy.html

> The Tar-Pamlico Nutrient Trading Program is a pioneering effort to more effectively manage nutrient inputs to an estuary. This paper discusses some of the technical work that supports Program implementation. In order to help the Program participants set a reasonable cost for trading nitrogen or phosphorus between point and nonpoint sources and understand how cost effective different BMPs are, we developed cost-effectiveness estimates (expressed as $/kilogram of nutrient load reduced) for cost-shared agricultural BMPs in the Basin.

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Mendez, A. (1999) Sediment and Nitrogen Transport in Grass Filter Strips 12. Journal Of The American Water Resources Association. Retrieved from the January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/publications/publications.htm?lognum=0000099349

Mohanty, B.P., U.S. Tim, C.E. Anderson, and T. Woestman. (1996) Impacts of Agriculture Drainage Well Closure on Crop Production: A Watershed Case Study. USDA/ARS. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/ttic/tektran/data/000007/32/0000073208.html

> In this study we simulated the water-logging condition in the watershed and the effect of excessive-water-stress on crop production following the closure of ADWs. A distributed modeling approach in conjunction with a geographical information system and crop stress models were used over a twenty year period. The results indicated that closure of ADWS in the watershed could result ponding in low-lying areas and poorly drained soils, making them unsuitable for crop production. Moreover, there is a 60 percent chance that crop yield loss in the watershed could exceed 18 percent for any year out of the twenty years considered in the study. Furthermore, our GIS-based modeling approach could give high resolution distributed maps for input parameters and simulation results, thus, helping the decision makers to focus on the problem areas.

Mostaghimi, S., V. Shanholz, T. Dillaha, A. Keiner, and B. Ross. (1987) Effects of Tillage System, Crop Residue Level, and Fertilizer Application Technique and Losses of Phosphorus and Pesticides from Agricultural Lands. VPI VWRRC Bulletin 157, Blacksburg, Virginia. NTIS PB 88-163837.

Mostaghimi, S., T.M. Younos, and U.S. Tim. (1992) Effects of Sludge and Chemical Fertilizer Application on Runoff Water Quality. Water Resources Bulletin 28(3):545-552. Abstract retrieved January 7, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.130059.4854.html

> Simulated rainfall was used on experimental field plots to compare the effect of chemical fertilizer and sludge application on sediment, nitrogen, and phosphorus in runoff from no-till and conventional-tillage systems. Chemical fertilizer application under the no-till system resulted in the least amount of total N and P in surface runoff. However, sludge application under the no-till system resulted in the least amount of NO3-N and sediment in surface runoff. The worst water quality scenarios were observed when either sludge or chemical fertilizer were surface-applied under a conventional tillage system.

Mostaghimi, S., T.M. Younos, and U.S. Tim. (1992) Crop Residue Effects on Nitrogen Yield in Water and Sediment Runoff from Two Tillage Systems. Agriculture Ecosystems and Environment 39:187-196.

Mumm, A. and S. Heathcote. (1997) Agricultural Drainage Wells: Solutions Through Public Policy. Paper presented at Midwest Groundwater Conference, Coralville, Iowa. October 23-24, 1997.

Nakao, M., B. Sohngen, L. Brown, and B. Leeds. (1999) The Economics of Vegetative Filter Strips. Ohio State University Extension, Agricultural Economics. Retrieved January 7, 2002 from the World Wide Web: http://ohioline.osu.edu/ae-fact/0006.html

> Benefits of vegetative filter strips need to be compared with the installation and maintenance costs. This publication provides general background on economic considerations associated with installing vegetative filter strips. It is intended for farmers and landowners, as well as technical and regulatory agency personnel. Contemporary data on benefits and costs are included to help farmers assess the financial aspects of filter strips. Four particular options are considered in this fact sheet: grass and legumes, hay, low managed timber, and high managed timber. The financial aspects of these options are then compared using average benefit and cost data for Ohio.

National Engineering Handbook, Part 651. (1992) Agriculture Waste Management Field Handbook. Chapters 1-11. U.S. Soil Conservation Service, Washington, DC, Engineering Division.

Park, S.W., S. Mostaghimi, R.A. Cooke, and P.W. McClellan. (1994) BMP Impacts on Watershed Runoff, Sediment, and Nutrient Yields. Water Resources Bulletin 30:1011-1023. Abstract retrieved January 8, 2002 from the World Wide Web:. http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

> To quantify the effectiveness of BMP implementation on runoff, sediment, and nutrient yields from a watershed, in Westmoreland County, Virginia. The changes in nonpoint source loadings resulting from BMPs were evaluated by comparing selected parameters from data series obtained before, during, and after periods of BMP implementation. The results indicated that the watershed-averaged curve number, sediment, and nutrient (N and P) concentrations were reduced by approximately 5, 20, and 40 percent, respectively, due to BMP implementation. Seasonal changes in nutrient availability factors were not consistent with field conditions, nor were they significantly different in the pre- and post-BMP periods. An extended period of monitoring, with intensive BMP implementation over a larger portion of the watershed, is required to identify RMP effectiveness.

Parsons, J.E., J.W. Gilliam, R. Munoz-Carpena, R.B. Daniels, and T.A. Dillaha. (1994) Nutrient and Sediment Removal by Grass and Riparian Buffers. American Society of Agricultural Engineers. Environmentally Sound Agriculture: Proceedings of the Second Conference, April 20-22, 1994. pp. 147-154.

Patni, N.K., L. Masse, and P.Y. Jui. (1998) Groundwater Quality Under Conventional and No Tillage: I. Nitrate, Electrical Conductivity, and pH. Journal of Environmental Quality 27(4):869-877.

Pocknee, S. and B. Boydell. (1995) Soil Sampling for Precision Farming. National Environmentally Sound Production Agriculture Laboratory, College of Agricultural and Environmental Sciences, University of Georgia, Athens, Georgia.

Pritchard, T.W., J.G. Lee, and B.A. Engel. (1993) Reducing Agricultural Sediment: An Economic Analysis of Filter Strips Versus Micro-targeting. Water, Science and Technology 28: 561-568.

Quade, D.J. and L.S. Seigley. (1997) Agricultural Drainage-Well Closures and Groundwater Quality Response: Floyd Country, Iowa. Interim Status Report to Iowa Department of Agriculture and Land Stewardship.

Qui, Z. and T. Prato. (1998) Economic Evaluation of Riparian Buffers in an Agricultural Watershed. Journal of the American Water Resource Association 34(4):877-890. Abstract retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/ResourceGuide.html

> This study determines the most cost effective spatial pattern of farming systems for improving water quality and evaluates the economic value of riparian buffers in reducing agricultural nonpoint source pollution in a Midwestern agricultural watershed. Economic and water quality impacts of alternative farming systems are evaluated using the CARE and SWAT models, respectively. Results strongly support efforts that encourage farmers to develop or maintain riparian buffers adjacent to streams.

Randall, G., D. Mulla, G. Rehm, L. Busman, J. Lamb, and M. Schmitt. (1998) Phosphorous: Transport to and Availability in Surface Waters. College of Agricultural, Food, and Environmental Science, University of Minnesota Extension Service. OF-6796-GO. Retrieved January 9, 2002 from the World Wide Web: http://www.extension.umn.edu/distribution/cropsystems/DC6796.html

Rausch, J. and B. Sohngen. (1997) Incentive Programs for Improving Environment Quality. Ohio State University Extension, Agricultural Economics. Retrieved January 7, 2002 from the World Wide Web: http://ohioline.osu.edu/ae-fact/0001.html

Ribaudo, M.O., R.D. Horan, and M.E. Smith. (1999) Economics of Water Quality Protection from Nonpoint Sources: Theory and Practice. Agricultural Economic Report No. 782, 120 pp. Retrieved January 14, 2002 from the World Wide Web: http://www.ers.usda.gov/publications/aer782/

Safley, L.M., Jr., P.W. Westerman, and L.D. King. (1989) Effects of Dairy Manure Application Rate and Timing, and Injector Spacing and Type on Corn Silage Production. Elsevier Science Publishers, Essex. Biological Wastes 28(3):203-216.

Schepers, J.S. (1987) Effect of Conservation Tillage on Processes Affecting Nitrogen Management. *In*: Effects of Conservation Tillage on Groundwater Quality: Nitrates and Pesticides, Terry J. Logan et al. (Editors). Lewis Publishers, Chelsea, Michigan, pp. 241-250.

Schmitt, M. and G. Rehm. (1998) Fertilizing Cropland with Poultry Manure. OF-5881-GO. University of Minnesota, St. Paul.

Schnabel, R. (2000) Improving Water Quality Using Native Grasses. Eastern Native Grasses Symposium. Retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/publications/publications.htm?lognum=0000108867

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. (1994) Managing Agricultural Phosphorus for Protection of Surface Waters: Issues and Options. Journal of Environmental Quality 23(3):437-451. Abstract retrieved January 7, 2002 from the World Wide Web:http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.171723.5176.html

> The main issues facing the establishment of economically and environmentally sound P management systems are the identification of soil P levels that are of environmental concern; targeting specific controls for different water quality objectives within watersheds; and balancing economic with environmental values. In developing effective options , we have brought together agricultural and limnological expertise to prioritize watershed management practices and remedial strategies to mitigate nonpoint-source impacts of agricultural P. Options include runoff and erosion control and P-source management, based on eutrophic rather than agronomic considerations. Current soil test P methods may screen soils on which the aquatic bioavailability of P should be estimated.

Sharpley, A.N. and P.J.A. Withers. (1996) The Environmentally-Sound Management of Agricultural Phosphorus. Fertilizer Research 39(2):133-146. Abstract retrieved January 8, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.174057.13289.html#6212

> The processes controlling the build-up of P in soil, its transport in surface and subsurface drainage in dissolved and particulate forms, and their biological availability in freshwater systems, are discussed in terms of environmentally sound P management. Such management will involve targeting cost-effective remedial measures to minimize P losses and accounting for different water quality objectives within watersheds. The means by which this can be achieved are identified and include developing soil tests to determine the relative potential for P enrichment of agricultural runoff to occur.

Sharpley, A.N. (1997) Rainfall Frequency and Nitrogen and Phosphorus Runoff from Soil Amended with Poultry Litter. Journal of Environmental Quality 26(4):1127-1132. Abstract Retrieved January 14, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.171723.5176.html

> The main factors affecting N and P runoff from land receiving manure include the rate, method, and timing of application. Of these factors, least information is available on timing; thus, the effect of rainfall frequency and timing after poultry litter application on N and P concentrations in runoff was investigated for 10 Oklahoma soils. Runoff N and P concentrations decreased with 10 successive rains, starting 7 days after litter application. Increasing the time between litter application and rainfall reduced total N, ammonium-N, and BAP by leaching and volatilization of N and sorption of P. Nitrate-N concentrations were unaffected by rainfall frequency and timing. Runoff N and P may be reduced by avoiding litter applications during periods of high rainfall probabilities, with these reductions greater for high P sorbing soils.

Sharpley, A.N., B. Foy, and P. Withers. (2000) Practical and Innovative Measures For the Control of Agricultural Phosphorus Losses to Water: An Overview. Journal of Environmental Quality 29(1):1-9. Retrieved January 8, 2002 from the World Wide Web: http://home.wlu.edu/~blackmerh/bio182/pfiesteria.html

> This paper provides a brief overview of P management strategies to maintain agricultural production and protect water quality that were discussed at the conference, "Practical and Innovative Measures for the Control of Agricultural Phosphorus Losses to Water," sponsored by the Organization for Economic Cooperation and Development and held in Antrim, Northern Ireland, June 1998.

Srivastava, P., D.R. Edwards, T.C., Daniel, P.A. Moore, Jr., T.A. Costello, and D.J. Nichols. (1996) Vegetative Filter Strip Performance with Varying Pollutant Source and Filter Strips Length. U.S. Department of Agriculture/ARS. Abstract retrieved January 7, 2002 from the World Wide Web: http://www.nal.usda.gov/ttic/tektran/data/000006/70/0000067083.html

> Small plot studies are often criticized as not being relevant to what really happens in the field. One example is research conducted on the amount of buffer strip needed to reduce non-point source nutrient runoff. In this research, the amount of area that is fertilized is usually much smaller than the downslope plots which act as the buffer areas. The objective of this study was to determine the combined influences of pollutant source area and vegetative buffer strip length on removal of nutrients from runoff water from plots which were simulating pastures. The results indicated that the area treated with manure did not affect the nutrient concentrations reaching the buffer plots, however, the mass of nutrients increased because the volume of water increased as the area treated with manure increased. Effectiveness of the buffer strips varied with type of nutrient and ranged from 6.5 to 96.3% removal.

Supalla, R.J., R.A. Selley, S. Bredeweg, and D. Watts. (1995) Adoption of Nitrogen and Water Management Practices to Improve Water Quality. Journal of Soil and Water Conservation 50:77-82.

Sweeney, D.W. and G.L. Kilgore. (2001) Integrated Agricultural Management Systems: Neosho River Basin Site. *In*: Kansas Fertilizer Research 2001: Report of Progress 885. Kansas State University Agricultural Experiment Station and Cooperative Extension Service. pp. 24-25. Retrieved January 7, 2002 from the World Wide Web: http://www.oznet.ksu.edu/library/crpsl2/srp885.pdf

Tauer, L.W. (1988) Economic Impacts of Agriculture Technologies That Affect Water Quality. New York's Food and Life Sciences Quarterly. New York Agricultural Experiment Stations and New York State College of Agriculture and Life Sciences, Ithaca, New York. 18(1/2):27-28.

Tobin, G.A. and R. Rajagopal. (1990) Expert Opinion and Groundwater Quality: The Case of Agricultural Drainage Wells. Journal of Soil and Water Conservation 45(2):336-342.

Torbert, H. (1999) Precision Farming Effects on Corn Productivity and Water Quality. International Conference on Geospatial Information. *In*: Agriculture and Forestry. Retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/publications/publications.htm?lognum=0000107813

Uri, N. (1999) The Economic Costs and Benefits of Conservation Tillage. Journal of Sustainable Agriculture 15(1):5-27. Abstract retrieved January 9, 2002 from the World Wide Web: http://bubl.ac.uk/journals/agr/jsusagr/v15n0199.htm#the%20economic

> The economic benefits of the adoption of conservation tillage depend on site-specific factors including soil characteristics, local climatic conditions, cropping patterns, and other attributes of the overall farming operation. While it is possible to draw some general inferences about components of economic returns and costs, a comprehensive assessment of the net private benefits from greater use of conservation tillage is not feasible.

USDA/ARS. (2001) Cost/benefit Analysis of Agricultural BMPs for Sediment Reduction in the Mississippi Delta. Retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/publications/publications.htm?lognum=0000121968

Verchot, L.V., E.C. Franklin, and J.W. Gilliam. (1997) Nitrogen Cycling in Piedmont Vegetated Filter Zones: I. Surface Soil Processes. Journal of Environmental Quality 26(2):327-336. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/short_list.022555.15603.html

The objective of this study was to evaluate the effectiveness of two forested filter zones (FFZ) for removing N from runoff in the Piedmont region of North Carolina.

Walker, D.J., B.L. Calkins, and J.R. Hamilton. (1993) Marginal Cost Effectiveness Analysis for Agricultural Nonpoint Source Water Quality Control. Journal of Soil and Water Conservation 48:368-372. *In*: The Special Edition: The Next Generation of U.S. Agricultural Conservation Policy. Paper Presented at the Conference "The Next Generation of U.S. Agricultural Policy", March 14-16, Kansas City, Missouri.

Webster, C.P. and K.W.T. Goulding. (1995) Effect of One Year Rotational Set-Aside on Immediate and Ensuing Nitrogen Leasing Loss. Plant and Soil 177(2):203-209.

Weiss, M. D. (1997) Phosphorus Fertilizer Application Under Precision Farming: A Simulation of Economic and Environmental Implications. Precision Agriculture '97 Papers Presented at the First European Conference on Precision Agriculture, Warwick University Conference Centre, UK, September 7-10, 1997. pp. 967-974. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/ResourceGuide.html

Wetselaar, R. (1974) Increasing the Efficiency of Nitrogen Fertilizers and Minimizing Losses to the Environment. Journal of Environmental Quality of Agricultural Science, Sydney. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.191405.14376.html#15

Review of the use of type, rate and timing of fertilizer application, and crop management history as factors to predict fertilizer efficiency.

White, S.K., H.F. Cook, and J.L. Garraway. (1998) The Use of Fertilizer-Free Grass Buffer Strips to Attenuate Nitrate Input to Marshland Dykes. Water Environmental Management Journal. CIWEM 12(1):54-59.

Wu, J.J. and B.A. Babcock. (1998) The Choice of Tillage, Rotation, and Soil Testing Practices: Economic and Environmental Implications. American Journal of Agricultural Economics 80(3): 494-511. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/ResourceGuide.html

Often adoption decisions about many practices are made simultaneously, which suggests use of a polychotomous-choice model to analyze decisions. Such a model is applied to the choice of alternative management practices on cropland in the Central Nebraska

Basin and controlled for self-selection and the interaction between alternative practices. The results of the choice model are used to estimate the economic and environmental effects of adopting alternative combinations of management practices.

Yadav, S.N. and D.B. Wall. (1998) Benefit-Cost Analysis of Best Management Practices Implemented to Control Nitrate Contamination of Groundwater. Water Resources Research 34(3):497-504. Abstract retrieved January 14, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/ResourceGuide.html

In this paper we evaluate water quality improvement by benefit-cost analysis of adopting BMPs under such a program. The analysis shows that under current levels of contamination, costs of the program to foster BMP implementation will be equal to annually accrued benefits over a period of 6 years. However, under the worsening scenarios of increased nitrate-N concentrations, the same costs will be equal to the benefits in a 4- to 5-year period. If water quality improves to acceptable levels through adoption of BMPs, the results reveal that in the long run, investing in a BMP program will be more cost effective to reduce contamination than to seek alternative sources of safe drinking water supplies.

Ongoing Research

Follett, R., J. Delgado, W. Hunter, A. Halvorson, and A. Mosier. Improving Soil and Nitrogen Management Systems for Sustaining Land and Water Quality. USDA/ARS. Project No. 5402-12130-007-00. To be completed by May 2006. Abstract retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/projects/projects.htm?accession=404640

Mostaghimi, S.R. B. Reneau, D. Bosch, J.A. Burger, and S. Shukla. A Framework For Evaluating BMP Effects On N And P Discharges From Watersheds. Duration: Two years. Departments of Biological Systems Engineering, Crop and Soil Environmental Sciences, Agricultural and Applied Economics, and Forestry, respectively, at Virginia Tech. Water Resources Research Act Grant.

This research proposes to study the impact of BMPs in a Virginia Coastal Plain watershed by employing the mass balance modeling approach. The project team will construct and analyze the watershed level N and P mass balances for crop season, annual, and crop rotation time scales, using the ten year (1986-1996) monitoring data collected at the Nomini Creek watershed in the Virginia Coastal Plain. The lessons learned from this study will be utilized to develop a framework for evaluating the watershed-scale BMP impacts. The results of this study could answer the following questions concerning effects of BMPs at the watershed scale and the role of atmospheric deposition as a nonpoint source of N and P, in the Chesapeake Bay drainage basin: a) were the BMPs sufficient to cause the change in surface and groundwater quality or did the response to BMPs occurred due to variability in precipitation and atmospheric N and

P loadings; b) what is the lag time for surface and groundwater response to BMPs; c) what improvements can be made in future studies aimed at evaluating BMP responses at watershed scale using the framework developed in this study; d) what is the economic impact of BMP implementation on farmer's net returns; e) what is the relative contribution of atmospheric deposition as a source of N and P in forested and mixed land use watersheds; and f) what is the extent of the temporal variability in the atmospheric and agricultural sources of N and P.

Site-Specific Management Center at the School of Agriculture, Purdue University. http://mollisol.agry.purdue.edu/SSMC/

Website contains the latest developments and technologies associated with precision farming.

South Florida Restoration Science Forum and USGS. Everglades Agricultural Area Experience: Overview of Phosphorus BMP Implementation. Retrieved October 22, 2001 from the World Wide Web: http://sofia.usgs.gov/sfrsf/rooms/sustain/management

This presentation on the South Florida Restoration Science Form describes BMPs implemented. Their effects on crop production and water quality are currently under investigation.

Pesticide Use

Recent Research

Anderson, S.H. and H.V. Kazemi. (1988) Field Variability of Atrazine Leaching Under No-Till Management. American Society of Agricultural Engineers, Paper No. 88-2641. St. Joseph, Michigan. 19 pp. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.101002.3339.html

Distribution of atrazine and bromide were measured in the 0 to 1.5 m depth in alluvial soils under no-till management. Although extreme variability in atrazine concentrations occurred, variations were not explained totally be differences in measured soil physical properties.

Arora, K., S.K. Mickelson, J.L. Baker, and D.P. Tierney. (1993) Evaluating Herbicide Removal by Buffer Strips Under Natural Rainfall. American Society of Agricultural Engineers, Paper No. 93-2593. 16 pp. Paper presented at the "1993 International Winter Meeting of the American Society of Agricultural Engineers," December 14-17, 1993, Chicago, Illinois. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

Arora, K., S.K. Mickelson, and J.L. Baker. (1995) Evaluating Vegetative Buffer Strips for Herbicide Retention. American Society of Agricultural Engineers, Paper No. 95-2699.

Arora, K., S.K. Mickelson, J.L. Baker, D.P. Tierney, and C.J. Peter. (1996) Herbicide Retention by Vegetative Buffer Strips from Runoff Under Natural Rainfall. Transactions of the American Society of Agricultural Engineers 30(6):2155-2162.

Baker, J.L. and H.P. Johnson. (1979) The Effect of Tillage System on Pesticides in Runoff from Small Watershed. Transactions of American Society of Agricultural Engineers 22:554-559.

Baker, J.L. and L.E. Shiers. (1990) Effects of Herbicide Formulation and Application Method on Washoff From Corn Residue. Transactions of the American Society of Agricultural Engineers 32(3):830-833. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.105228.3383.html

> Herbicides were broadcast-sprayed on trays of corn residue that were then subjected to simulated rainfall. Cyanazine washoff was not affected by formulation (liquid, wettable-powder, or dry-flowable) or by method of application (with water or oil-water mixtures). Method of application also did not affect washoff of the liquid formulations of alachlor and propachlor tested. Most of the washoff occurred with the first 14.5 mm increment of rain.

Baker, J.L. and S.K. Mickelson. (1994) Application Technology and Best Management Practices for Minimizing Herbicide Runoff. Weed Technology 8(4):862-869.

Basta, N.T., R.L. Huhnke, and J.H. Stiegler. (1997) Atrazine Runoff from Conservation Tillage Systems: A Simulated Rainfall Study. Journal of Soil and Water Conservation 52(1):44-48.

Berryhill, W.S., Jr., A.L. Lanier, and M.D. Smolen. (1989) The Impact of Conservation Tillage and Pesticide Use on Water Quality: Research Needs. *In*: Pesticides in Terrestrial and Aquatic Environments. Proceedings of National Research Conference, May 11-12, 1989. Blacksburg, Virginia, pp. 397-404.

Bode, L.E. (1990) Agricultural Chemical Application Practices to Reduce Environmental Contamination. Amer. J. Ind. Med. 18(4):485-489. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.104227.3377.html

> Improved methods of application and ways of reducing the total amount of pesticide applied can help reduce environmental contamination. Chemigation, direct injection, closed system handling, and fertilizer impregnation are types of technology that affect the efficiency of applying agricultural chemicals. Current surveys indicate that point

sources such as spills, mixing, and loading areas, back-siphoning, and direct routes for surface water movement into the ground are often a major cause of pesticides reaching groundwater. Education remains an important element of any rural environmental health strategy.

Boyd, P.M., L.W. Wulf, J.L. Baker, and S.K. Mickelson. (1999) Pesticide Transport Over and Through the Soil Profile of a Vegetative Filter Strip. American Society of Agricultural Engineers, Paper No. 99-2077.

Brinsfield, R.N., K.W. Staver, and W.L. Magette. (1988) Leaching of Pesticides in Coastal Plain Soils as Influenced by Tillage System. American Society of Agricultural Engineers, Paper No. 88-2650. 16 pp. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.113348.3438.html

The movement of atrazine, cyanazine, simazine, and metolachlor, were monitored under continuous conventional-till (CT) and non-till (NT) corn cropping systems. Results suggest that is significant precipitation occurs within two months of application, the pesticides considered in this study can leach to ground water. Results suggest that NT systems may provide a matrix for more rapid water transmission through the root zone than CT systems.

Castelle, A.J., A.W. Johnson, and C. Conolly. (1994) Wetland and Stream Buffer Size Requirements – A Review. Journal of Environmental Quality 23:878-882.

Christensen, B. (1992 or 1993) BMPs for Water Quality: Best Management Practices to Reduce Runoff of Pesticides into Surface Water: A Review and Analysis of Supporting Research. Conservation Technology Information Center. 43 pp. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

Christensen, B., J.M. Montgomery, R.S. Fawcett, and D. Tierney. (1993) BMPs For: Water Quality Reducing Herbicide Runoff: Role of Best Management Practices. Conservation Technology Information Center, WQBMP2-0993-10K.

CIBA-GEIGY Corp. (1992) Reducing Herbicide Runoff: Role of Best Management Practices. Technical Report 10-92. CIBA-GEIGY Corporation, Environmental and Public Affairs Department, Agricultural Division, Greensboro, North Carolina. 15 pp.

Clausen, J.C., W.E. Jokela, F.I. Potter III, and J.W. William. (1996) Paired Watershed Comparison of Tillage Effects on Runoff, Sediment, and Pesticide Losses. Journal of Environmental Quality 25(5):1000-1007. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

A paired watershed study was used to compare runoff, sediment, atrazine, and cyanazine losses from conventional-tilled (CT) and reduced-tilled (RT) corn watersheds. During a 30-mo treatment period, one watershed was moldboard plowed while the other was disk harrowed. Reduced tillage decreased runoff by 64% and sediment losses by 99% but did not change dissolved atrazine or cyanazine concentrations in runoff. Concentrations of sediment-sorbed pesticides increased in runoff. The RT reduced mass losses of atrazine and cyanazine in runoff, primarily because of decreases in runoff volume and sediment mass. Most pesticide losses occurred within 3 wk of field application. Pesticide loss was primarily in the dissolved phase. The paired watershed approach was a useful technique for determining watershed treatment effects when differences existed between watersheds chosen for study.

Cole, J.T., J.H. Baird, N.T. Basta, R.L. Huhnke, D.E. Storm, G.V. Johnson, M.E. Payton, M.D. Smolen, and D.L. Martin. (1997) Influence of Buffers on Pesticide and Nutrient Runoff from Bermudagrass Turf. Journal of Environmental Quality 26(6):1589-1598.

Fawcett, R.S., B.C. Christensen, and J.M. Montgomery. (1992) Best Management Practices to Reduce Runoff of Pesticides into Surface Water: A Review and Analysis of Supporting Research. CIBA-GEIGY Corporation, Agricultural Group. Technical Report: 9-92. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

This report summarizes current research on the effectiveness of BMPs such as filter strips, no-till, subsurface drainage, waterways, and improved timing of applications at reducing pesticide runoff from fields. The report also presents the scope and sources of the pesticide problem in surface waters.

Fawcett, R.S., B.R. Christensen, and D.P. Tierney. (1994) The Impact of Conservation Tillage on Pesticide Runoff into Surface Water: A Review and Analysis. Journal of Soil and Water Conservation 49(2):126-135. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

This article combines soils and monitoring data from a number of studies to provide a comparison of pesticide runoff from no till, disked, ridge till, and chisel plots under several rainfall schemes. Data are presented for at least 8 herbicides and 4 to 5 residue covers. The article concludes by stating that the adoption of conservation tillage should reduce the risk of undesirable impacts of pesticides on human and aquatic health.

Felsot, A.S., J.K. Mitchell, and A.L Kenimer. (1990) Assessment of Management Practices for Reducing Pesticide Runoff from Sloping Cropland in Illinois. Journal of Environmental Quality 19(3):539-545. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.105228.3383.html

> Our experiments using small plot and simulated rainfall showed that conservation tillage systems significantly reduced runoff losses of alachlor, carbofuran, and terbufos. Contouring alone significantly reduced pesticide runoff regardless of tillage system. Alachlor losses in the water phase of NT plots oriented up-and-down slope were numerically larger than those from other reduced tillage systems. Differences between rainfall amounts, ambient soil conditions, and soil could account for the relative differences in alachlor runoff among tillage systems. Contoured ST and NT yielded the least amount of runoff, sediment, and consequently, pesticide. We noted that no conservation tillage system completely eliminated pesticide runoff. At best, we significantly reduced the runoff of pesticides by using agronomic management practices. Such practices must focus on controlling water runoff as well as soil erosion.

Fermanich, K.J., W.L. Bland, B. Lowery, and K. McSweeney. (1996) Irrigation and Tillage Effects on Atrazine and Metabolite Leaching from a Sandy Soil. Journal of Environmental Quality 25(6):1291-1299. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

> The rate and amount of atrazine movement through a sandy soil was measured as a site along the Lower Wisconsin River Valley in Iowa County, Wisconsin, during the 1991 and 1992 growing seasons. Three irrigation water management regimes were compared: no-irrigation, irrigation according to water balance, and surplus irrigation.

Foy, C.L. and H. Hiranpradit. (1989) Movement of Atrazine by Water from Application Sites in Conventional and No-Tillage Corn Production. *In*: Pesticides in Terrestrial and Aquatic Environments Proceedings. NIA Water Resources Research Center, VPI & State University. pp. 355-377. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.101002.3339.html

> Results of this study indicated that overall the no-tillage practice gave higher yields and greatly minimized runoff of herbicidal chemical as well as eroded sediment. Contamination of natural water resources by surface runoff of atrazine can thus be kept to the minimum by adoption of the no-tillage approach to corn production.

Franti, T.G., C.J. Peter, D.P. Tierney, R.S. Fawcett, and S.A. Meyers. (1995) Best Management Practices to Reduce Herbicide Losses from Tile-outlet Terraces. American Society of Agricultural Engineers, Paper No. 95-2713. St. Joseph, Michigan.

Franti, T.G., C.J. Peter, D.P. Tierney, R.S. Fawcett, and S.A. Meyers. (1998) Reducing Herbicide Losses from Tile-Outlet Terraces. Journal of Soil and Water Conservation 53(1):25-31.

Gish, T.J., A.R. Isensee, R.G. Nash, and C.S. Helling. (1991) Impact of Pesticides on Shallow Groundwater Quality. Transactions of the American Society of Agricultural Engineers 34(4):1745-1753. Abstract retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9366.html

> A three-year field study was initiated in 1986 to determine the impact of tillage practice, mode of pesticide application, and pesticide formulation on chemical transport. The field site was divided into four plots, two each devoted to no-till and conventional tillage management. Pesticide transport was evaluated by monitoring the rate of change in concentrations of pesticides in a shallow perched water table. Pesticides monitored included atrazine, alachlor, cyanazine and carbofuran. All three herbicides were applied as a single broadcast spray: granular insecticide carbofuran was band- injected at planting.

Gish, T. J., A. Shirmohammadi, R. Vyravipillai, and B.J. Wienhold. (1995) Herbicide Leaching Under Tilled and No-tillage Fields. Soil Science Society of America 59(3):895-901. Abstract retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

> The effect of no-tillage practices on water quality exiting the root zone of a deep, well drained field is largely unknown. This project was initiated to determine herbicide leaching characteristics as influenced by tillage practice and herbicide formulation.

Glenn, S. and J.S. Angle. (1987) Atrazine and Simazine in Runoff from Conventional and No-Till Corn Watersheds. Agricultural Ecosystems and Environment 18:273-280.

Grisso, R.D., E.J. Hewett, E.C. Dickey, R.D. Schneider, and E.W. Nelson. (1988) Calibration Accuracy of Pesticide Application Equipment. Applied Engineering in Agriculture 4(4):310-315. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.140949.3685.html

> A field survey of 140 private and commercial pesticide applicators was conducted during the spring of 1986 in 12 counties of central and eastern Nebraska. The results showed that one out of every three cooperators was applying pesticides within + or - 5% of their intended application rate. However, most errors still can be traced to incorrect calibration.

Hall, J.K., N.L. Hartwig, and L.D. Hoffman. (1983) Application Mode and Alternate Cropping Effects on Atrazine Losses from a Hillside. Journal of Environmental Quality 12(3):336-340.

Abstract retrieved January 10, 2002 from the World Wide Web:
http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.101002.3339.html

> In Plot studies in Pa. it was found that atrazine losses from a 2.2 Kg/ ha application were reduced 91% when a 6 meter strip of oats was planted at the base of the plot. Water and soil losses were decreased by 66% and 76% respectively. Herbicide loss reduction is concomitant with a decrease in runoff volume. When a 4.5 kg/hr application rate was used, a 65% reduction in atrazine runoff was observed. The authors note that these conventionally tilled systems with some pre-plot incorporation can reduce herbicide losses to an extent comparable with tilled systems.

Hall, J.K., M.R. Murray, and N.L. Hartwig. (1989) Herbicide Leaching and Distribution in Tilled and Untilled Soil. Journal of Environmental Quality 18:439-445. Abstract retrieved January 18, 2002 from the World Wide Web:
http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

> Leaching and distribution of several pesticides were evaluated in a silty clay loam soil under conventional tillage (CT) and no-tillage (NT) corn management. In general, maximum herbicide concentrations detected and mean total amounts were greater under NT conditions where more leachate was collected each year than in CT. Where worst-case conditions were considered, mean leaching losses (simazine, atrazine) were 0.15 kg/ha, therefore, at least 91% was retained and/or degraded within the soil profile or in the corn tissue after absorption. Simazine and atrazine were the most persistent and mobile herbicides, and were consistently detected at all soil depths to 122 cm.

Hall, J.K., R.O. Mumma, and D.W. Watts. (1991) Leaching and Runoff Losses of Herbicides in a Tilled and Untilled Field. Agricultural Ecosystems and Environment 37(4):303-314.

Hamilton, P.B., D.R.S. Lean, G.S. Jackson, N.K. Kaushik, and K.R. Solomon. (1989) The Effect of Two Applications of Atrazine on the Water Quality of Freshwater Enclosures. Environmental Pollution 60:291-304.

Hoffman, D.W. (1995) Use of Contour Grass and Wheat Filter Strips to Reduce Runoff Losses of Herbicides. Proceedings of the Austin Water Quality Meeting, Texas A & M University, Temple, Texas.

Hoffman, D.W. and T. Gerik. (1995) Limiting Herbicide Runoff with Vegetative Filter Strips. Texas Agricultural Experiment Station, Blackland Research Center, Temple, Texas. NewWaves 8(3). Retrieved January 4, 2002 from the World Wide Web:
http://twri.tamu.edu/twripubs/NewWaves/v8n3/abstract-4.html

Hoffman, D.W., J.E. Wolfe, S.A. Senseman and K.N. Potter. (1998) Effectiveness of Grass Filter Strips to Reduce Atrazine in Simulated Runoff. International Congress of Pesticide Chemistry 6C-028.

Huang, L.Q. and J.F. Ahrens. (1991) Residues of Alachlor in Soil after Application of Controlled Release and Conventional Formulations. Bull. Environ. Contam. Toxicol. 47(3): 362-367.

Isensee, A.R., R.G. Nash, and C.S. Helling. (1990) Effect of Conventional vs. No-tillage on Pesticide Leaching to Shallow Groundwater. Journal of Environmental Quality 19:434-440. Abstract retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

> A field site was established at Beltsville, MD, in 1986 to assess the effect of conventional and no-till cultural practices on the movement of pesticides into shallow groundwater. Atrazine was found in groundwater all year, while cyanazine, alachlor, and carbofuran were present only for a short period (< 3 mo) after pesticide application. Pesticide residues in unconfined groundwater were usually higher than in confined groundwater. Rainfall timing relative to pesticide application was critically important to pesticide leaching. Results of this study suggest that preferential transport occurred.

Isensee, A.R. and A.M. Sadeghi. (1993) Impact of Tillage Practice on Runoff and Pesticide Transport. Journal of Soil and Water Conservation 48(6):523-527. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

> A two-year study was conducted to evaluate the effect of no-till (NT) and conventional-till (CT) corn production practices on pesticide loss in runoff from natural rainfall.

Isensee, A.R., and A.M. Sadeghi. (1995) Long-term Effect of Tillage and Rainfall on Herbicide Leaching to Shallow Groundwater. Chemosphere 30:671-685. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

Isensee, A.R. and A.M. Sadeghi. (1996) Effect of Tillage Reversal on Herbicide Leaching to Groundwater. Soil Science 161(9):382-389. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.113348.3438.html

> A 3-year field study was conducted to determine the effect of reversing the tillage of 7-year-old no-till (NT) and conventional-till (CT) plots on the leaching of atrazine, alachlor, and cyanazine to groundwater. Results confirm that NT increases herbicide leaching compared with CT and that several years are required for preferential pathways to develop under NT.

Kanwar, R.S., D.E. Stoltenberg, R. Pfeiffer, D.L. Karlen, T.S. Colvin, and M. Honeyman. (1991) Long-term Effects of Tillage and Crop Rotation on the Leaching of Nitrate and Pesticides to Shallow Groundwater. American Society of Civil Engineers. *In:* Irrigation and Drainage: Proceedings of the 1991 National Conference, Honolulu, Hawaii, July 22-26, 1991. pp. 655-661. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9366.html

Kanwar, R.S. and J.L. Baker. (1996) Tillage and Chemical Management Effects on Groundwater Quality. Agricultural Research to Protect Water Quality. Proceedings of Soil and Water Conservation Society. pp 455-459.

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. (1997) Ridge, Moldboard, Chisel, and No-Till Effects on Tile Water Quality Beneath Two Cropping Systems. Journal of Production Agriculture 10(2):227-234.

Lee, K.H. (1997) Nutrient and Sediment Removal by Switchgrass and Cool-Season Grass Filter Strips. *In*: Proceedings of Vegetative Filter Strip and Riparian Buffer Research Symposium, December 17, 1997, University of Nebraska, Lincoln.

Levanon, D., E.E. Codling, J.J. Meisinger, and J.L. Starr. (1993) Mobility of Agrochemicals through Soil from Two Tillage Systems. Journal of Environmental Quality 22(1):155-161. Abstract retrieved January 10, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.133500.3626.html

> This study was conducted to characterize the impact of two contrasting tillage systems on the movement of agrochemicals in soil. The two tillage systems were plow-tillage (PT) and no-tillage (NT) for corn production. Nitrate leaching was significantly greater under PT than NT. The pesticide movement also tended to be greater under PT than NT. Caution should be exercised in generalizing to field conditions, but these data suggest that there can be greater leaching losses on surface-applied agrochemicals to ground water under PT than under NT.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman, J.M. Denver, D.L. Correll, J.W. Gilliam, J.L. Robinson, R.S. Brinsfield, K.W. Staver, W. Lucas, and A.H. Todd. (1995) Water Quality Functions of Riparian Forest Buffer Systems in the Chesapeake Bay Watershed. EPA 903-R-95-004.

Lowrance, R., G. Vellidis, R.D. Wauchope, P. Gay, and D.D. Bosch. (1997) Herbicide Transport in a Managed Riparian Forest Buffer System. Transactions of the American Society of Agricultural Engineers 40(4):1047-1057.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. (1989) Nutrient and Sediment Removal by Vegetated Filter Strips. Transactions of the American Society of Agricultural Engineers 32(2):663-667.

Masse, L., N.K. Patni, P.Y. Jui, and B.S. Clegg. (1998) Groundwater Quality Under Conventional and No Tillage: II. Atrazine, Deethylatrazine, and Metolachlor. Journal of Environmental Quality 27(4):877-883.

Matter, M.P. (1993) Sorption Kinetics of Atrazine and Hydroxyatrazine in Freshwater Wetlands. M.S. Dissertation, Iowa State University, Ames, Iowa.

Meyer, L.D., S.M. Dabney, and W.C. Harmon. (1995) Sediment-trapping Effectiveness of Stiff-grass Hedge. Transactions of the American Society of Agricultural Engineers 38(3):809-815.

Mickelson, S.K. and J.L. Baker. (1993) Buffer Strips for Controlling Herbicide Runoff Losses. American Society of Agricultural Engineers, Paper No. 93-2084. St. Joseph, Michigan.

Mickelson, S.K., J.L. Baker, S.W. Melvin, R.S. Fawcett, D.P. Tierney, and C.J. Peter. (1998) Effects of Soil Incorporation and Setbacks on the Herbicide Runoff from a Tile-Outlet Terraced Field. Journal of Soil and Water Conservation 53(1):18-25.

Mielke, L.N. and J.R.C. Leavitt. (1981) Herbicide Loss in Runoff Water and Sediment as Affected by Center Pivot Irrigation and Tillage Treatment. U.S. Department of the Interior, Office of Water Research and Technology. Report A-062-NEB.

Milburn, D., D.A. Leger, H. O'Neill, K. MacQuarrie, and J.E. Richards. (1995) Point and Nonpoint Source Leaching of Atrazine from a Corn Field: Effects on Tile Drainage Water Quality. Canadian Agricultural Engineering 37(4):269-277.

Misra, A.K. (1994) Effectiveness of Vegetative Buffer Strips in Reducing Herbicide Transport with Surface Runoff Under Simulated Rainfall. Ph.D. Thesis. Iowa State University, Ames, Iowa.

Misra, A.K., J.L. Baker, S.K. Mickelson, and H. Shang. (1994) Effectiveness of Vegetative Buffer Strips in Reducing Herbicide Transport with Surface Runoff Under Simulated Rainfall. American Society of Agricultural Engineers, Paper No. 94-2146. St. Joseph, Michigan.

Misra, A.K., J.L. Baker, S.K. Mickelson, and H. Shang. (1996) Contributing Area and Concentration Effects on Herbicide Removal by Vegetative Buffer Strips. Transactions of the American Society of Agricultural Engineers 39(6):2105-2111.

Myers, J.L., M.G. Wagger, and R.B. Leidy. (1995) Chemical Movement in Relation to Tillage System and Simulated Rainfall Intensity. Journal of Environmental Quality 24(6):1183-1192. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.144759.3743.html

> Three tillage-residue management systems were compared for their effect on concentrations of atrazine, metolachlor, and bromide in surface runoff and in the soil profile of a Pacolet sandy clay loam (clayey, kaolinitic, thermic Typic Kanhapludults) These systems included conventional tillage (CT), no-tillage grain production with corn residue (NTG), and no-tillage silage production without residue (NTS).

Nicholaichuk, W. and R. Grover. (1983) Loss of Fall-Applied 2,4-D in Spring Runoff from a Small Agricultural Watershed. Journal of Environmental Quality 12(3):412-417. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.105228.3383.html

> Paper discusses the loss of 2,4-D after fall application to a stubble field as results from runoff. This loss is compared to a non-treated summer fallow field that was used as a control.

Norton, G.W. and J. Mullen. (1994) Economic Evaluation of Integrated Pest Management Programs: A Literature Review. Virginia Cooperative Extension Publication 448-120, Virginia Tech, Blacksburg, Virginia.

Olsen, L.D. (1995) Pesticide Movement in Soils: A Comparison of No-Tillage and Conventional Tillage in the Beaver Creek Watershed in West Tennessee. U.S. Geological Survey Open-File Report 95-329. Retrieved October 22, 2001 from the World Wide Web: http://tn.water.usgs.gov/pubs/OFR95-329/pesticide.html

> The objectives of this study were to develop a soil sampling strategy to accurately characterize the distribution of a selected pesticide in the soil profile, to measure the movement and degradation of the pesticide throughout the growing season, and to compare the behavior of the pesticide in no-tilled and conventionally tilled fields.

Pantone, D.J., K.N. Potter, H.A. Torbert, and J.E. Morrison, Jr. (1996) Atrazine Loss in Runoff from No-Tillage and Chisel-Tillage Systems on a Houston Black Clay Soil. Journal of Environmental Quality 25(3):527-577. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.105228.3383.html

> This study was conducted to determine how tillage impacts herbicide losses in runoff from a vertisol soil on the Blackland Prairie of Texas. Tillage treatments consisted of no-tillage or chisel-tillage. All experiments were repeated four times. No differences in atrazine concentrations were found among treatments in either the runoff water or sediment from any of the five time periods; however, crop residues prevented surface seal development and erosion resulting in reduced runoff and sediment yield, rather than the atrazine concentration of the runoff, resulting in a 42% decrease of the atrazine load in the runoff and a 77% decrease in atrazine associated with the sediment.

Patty, L., B. Real, and J.J. Gril. (1997) The Use of Grassed Buffer Strips to Remove Pesticides, Nitrate and Soluble Phosphorus Compounds from Runoff Water. Pesticide Science 49(3):243-251. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.141535.3693.html

> Literature data and conclusions drawn from previous work with isoproturon and diflufenican were confirmed in a range of soil and cropping conditions: grassed buffer strips are effective in restricting pollutant transfer in runoff; those with widths of 6, 12 and 18 m reduced runoff volume by 43 to 99%, suspended solids by 87 to 100%, lindane losses by 72 to 100% and loss of atrazine and its metabolites by 44 to 100%.

Pimentel, D., L. McLaughlin, A. Zepp, B. Lakitan, T. Kraus, P. Kleinman, F. Vancini, W.J. Roach, and E. Grasp. (1993) Environmental and Economic Effects of Reducing Pesticide Use in Agriculture. Agricultural Ecosystems and Environment 46:273-288.

Randhir, T.O. and J.G. Lee. (1997) Economic and Water Quality Impacts of Reducing Nitrogen and Pesticide Use in Agriculture. Agric. Resour. Econ. Rev. 26(1):39-51. Retrieved January 14, 2002 http://www.nal.usda.gov/wqic/ResourceGuide.html

Rankins, A., Jr., D.R. Shaw, M. Boyette, and S.M. Seifert. (1998) Minimizing Herbicide and Sediment Losses in Runoff with Vegetative Filter Strips. Abstracts Weed Sci. Soc. Am. 38:59.

Sabbagh, G.J., P.E. Norris, S. Geleta, D.J. Bernado, R.L. Elliott, H.P. Mapp, and J.F. Stone. (1992) Environmental and Economic Impacts of Pesticide and Irrigation Practices: EPIC-PST Simulation. American Society of Agronomy, Journal of Production Agriculture 5(3):312-317. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9366.html

Schultz, R.C., J.P. Colletti, T.M. Isenhart, W.W. Simpkins, C.W. Mize, and M.L. Thompson. (1995) Design and Placement of a Multi-species Riparian Buffer Strip System. Agroforestry Syst. 29:201-226.

Schultz, R.C., A. Kehl, J.P. Colletti, P. Wray, T. Isenhart, and L. Miller. (1997) Riparian Buffer Systems. Iowa State University Publication Pm-1626a, Ames Iowa.

Seta, A.K., R.L. Blevins, W.W. Frye, and B.J. Barfield. (1993) Reducing Soil Erosion and Agricultural Chemical Losses with Conservation Tillage. Journal of Environmental Quality 22:661-665.

Setia, P. and S. Piper. (1992) Effects of Soil and Agricultural Chemicals Management on Farm Returns and Ground Water Quality. Michigan State University. Review of Agricultural Economics 14(1):65-80. Abstract Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/qb9366.html

> Economic and physical simulation models were utilized to evaluate the effect of alternative soil and agricultural chemical management systems, implemented under the Conservation Reserve and Conservation Compliance Programs, on pesticides' leaching, and returns to fixed farm resources. Findings of the study show that the selection of appropriate soil and chemical systems may not only increase farm returns but may also result in a significant reduction in leaching and hence groundwater degradation.

Shaw, D.R., C.A. Smith, and J.E. Hairston. (1992) Impact of Rainfall and Tillage Systems on Off-Site Herbicide Movement. Comm. Soil Sci. Plt. Anal. 23(15/16):1843-1858. Abstract retrieved January 4, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.101002.3339.html

> This study was conducted in 1987 and 1988 to evaluate runoff losses of soil-applied alachlor and imazaquin in five different soybean cropping systems. Cropping systems used were: 1) conventionally tilled monocrop soybean planted in May; 2) conventionally tilled monocrop soybean planted in June; 3) conventionally tilled doublecrop soybean with incorporated wheat stubble; 4) no-till doublecrop soybean with burned wheat stubble; and 5) no-till doublecrop soybean planted into standing wheat stubble. Herbicide loss in both years was greatest in doublecrop soybean with incorporated wheat stubble, which corresponded to higher runoff. Lower herbicide loss in June-planted monocrop soybean was attributed to a rougher seedbed that retarded runoff. May-planted monocrop soybean also lost very little herbicide in 1987, although this treatment had the highest runoff. Lower concentrations of alachlor and imazaquin in runoff from this treatment may be attributed to degradation or soil sorption of herbicides between planting and the first runoff event 23 days later.

Shipitalo, M.J., W.M. Edwards, and L.B. Owens. (1997) Herbicide Losses in Runoff from Conservation-Tilled Watersheds in a Corn-Soybean Rotation. Soil Science Society of America 61(1):267-272. Abstract retrieved January 18, 2002 from the World Wide Web: http://h2osparc.wq.ncsu.edu/biblio/results/detail_list.105228.3383.html

> Soil and nutrient losses are tolerable when corn and soybean are grown in rotation on steep slopes in northern Appalachia if conservation tillage is used and a rye cover crop follows soybean harvest. Herbicide losses and concentrations in runoff resulting from this rotation, however, may be unacceptable. Therefore, runoff from two chiseled and two no-till watersheds was monitored for 4 yr to determine the effect of this cropping sequence on losses of four commonly used herbicides: alachlor, atrazine, linuron, and metribuzin. As a percentage of applied chemical, average losses were small with atrazine, linuron, metribuzin , alachlor. At times, however, herbicide concentrations may be a concern. Atrazine concentrations consistently exceeded the lifetime Health Advisory Level-Maximum Contaminant Level in the first few runoff events after application. In addition, atrazine was detectable in runoff during soybean years, at times above the HAL-MCL. Average linuron loss was significantly less than that of atrazine and linuron was rarely detected in runoff following corn harvest or during soybean years.

Shivankar, V.J. and V.S. Kavadia. (1992) Effect of Crop Rotation on the Persistence and Absorption of Heptachlor. Crop Research (HISAR) 5(1):134-140.

Smith, S., Jr. (1993) Effects of Tillage on Pesticide Concentrations in Shallow Ground Water and Surface Runoff from Fragipan Soils in North Mississippi, USA. *In*: Proceedings of Industrial and Agricultural Impacts on the Hydrologic Environment, the Second USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology, Alexandria, Virginia: Water Environment Federation. 2:79-91. Retrieved January 10, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html

Staddon, W.J., M.A. Locke, and R.M. Zablotowicz. (2001) Microbial Characteristics of a Vegetative Buffer Strip Soil and Degradation and Sorption of Metolachlor. Soil Science Society of America Journal. Abstract retrieved January 8, 2002 from the World Wide Web: http://soil.scijournals.org/cgi/content/abstract/65/4/1136?maxtoshow=&HITS=10&h

> Numerous studies have documented efficacy of vegetated buffer strips (VBS) in removing herbicides from surface runoff. Little is known about the fate of herbicides after deposition in buffer strip soil. Soil samples were collected from a buffer strip and an adjacent bare field (BF). Data suggest retention and enhanced degradation of metolachlor as it passes through VBS strips may limit further transport.

Tingle, C.H., D.R. Shaw, M. Boyette, and G.P. Murphy. (1998) Metolachlor and Metribusin Losses in Runoff as Affected by Width of Vegetative Filter Strips. Weed Science 46:475-479.

Watts, D.W. and J.K. Hall. (1996) Tillage and Application Effects on Herbicide Leaching and Runoff. Soil and Tillage and Res. 39(3/4):241-257.

Webster, E.P. and D.R. Shaw. (1996) Impact of Vegetative Filter Strips on Herbicide Loss in Runoff from Soybean (Glycine max). Weed Science 44:662-671.

Wolf, S.A. and P.J. Nowak. (1996) A Regulatory Approach to Atrazine Management: Evaluation of Wisconsin's Groundwater Protection Strategy. Journal of Soil and Water Conservation 51(1):94-100.

Ongoing Research

Moog, Douglas, Peter John Whiting, and Gerald Matisoff. Water Reduces Research Grant Proposal: Sediment Loads and Conservation Tillage in the Maumee River Watershed. USGS. To be completed March 2002. Retrieved October 22, 2001 from the World Wide Web: http://water.usgs.gov/wrri/01grants/OH2821.html

> In the Maumee River Basin, suspended sediment discharges tend to decrease as conservation tillage increased. The proposed project seeks to analyze this finding by use of a distributed, process-based model developed for this watershed. One inquiry will be to test whether conservation tillage could reasonably account for the observed sediment load decreased, and whether alternative variables, such as weather, might have contributed.

Potter, T., D. Bosch, and R. Wauchope. Best Management Practices to Protect Ground and Surface Water from Agricultural Chemicals in Sdb. USDA/ARS. To be completed April 2003. Abstract retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/projects/projects.htm?accession=404446

> Objective to determine pesticide and nutrient loading to groundwater; evaluated the efficacy of summer cover crops as water quality BMPs; assess the fate and transport of “indicator” pesticides; characterize hydraulic properties of the upper Biscayne aquifer; determine the viability of selected cover crops and compare the performance of three leaching models.

Shaw, David. Water Resources Research Grant Proposal: Benefits of Various Best Management Practices in Reducing Herbicides in Runoff Water. USGS. Completed February 2001. Retrieved October 22, 2001 from the World Wide Web: http://water.usgs.gov/wrri/99projects/state/Mississippi3.html

> This project evaluated the effects of a stiff-grass vegetative filter strip in conjunction with conventional and conservation tillage systems on off-site movement of two widely used soil-applied herbicides. Also, laboratory studies will determine herbicide adsorption and degradation in the filter strips, the treated fields, and at various intervals moving into the riparian forest at one of the watershed.

Shipitalo, Martin and Lloyd Owens. Management Effects on Water, Soil, Nutrient and Pesticide Losses from Cropped and Grazed Watersheds. USDA/ARS. Study to be completed by July 2002. Abstract retrieved January 4, 2002 from the World Wide Web: http://nps.ars.usda.gov/projects/projects.htm?accession=400072

> Transgenic, herbicide-tolerant corn and soybean will be grown using high- and reduced-input practices and losses of the current generation of herbicides in runoff and percolate will be compared to those of the post-emergence products. Multi-year applications of poultry litter on pastured watersheds and lysimeters will be used to determine the effects on surface and subsurface water quality and soil nutrient. The data will be used to evaluate and refine sediment and chemical transport models.

Combined and Sanitary Sewer Overflows

Recent Research

Bennett, D., R. Rowe, M. Strum, D. Wood, N. Schultz, K. Roach, and V. Adderley. (1999) Using Flow Prediction Technologies to Control Sanitary Sewer Overflows. WERF Project No. 97-CTS-8. Retrieved January 16, 2002 from the World Wide Web: http://www.werf.org/research/search

Boner, M.C., et al. (1994) Optimization of Vortex Separator Removal Efficiencies for CSO Treatment. WERF Project No. 92-TCR-2. Retrieved November 6, 2001 from the World Wide Web: http://www.werf.org/research/search/

> This project investigates the degree of contaminant removal by a modified vortex separator (MVS) Combined Sewer Overflow (CSO) control device using dissolved air flotation, UV disinfection, and/or chemical addition. Presents pollutant removal data for TSS, BOD5, COD, fecal coliform, and phosphorus. Due to a failure of the system, results are preliminary only; however, the MVS may be useful as a high-rate, efficient CSO treatment.

Brashear, R.W. Best Practices for Treatment of Wet Weather Flows. WERF Project No. 00-CTS-6. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

Moffa and Associates. (2001) Wet Weather Research Protocols. WERF Project No. 95-WWR-1A. Retrieved November 9, 2001 from the World Wide Web: http://www.werf.org/research/search/

> This project develops protocols to evaluate treatment and control technologies and associated benefits to receiving waters. The report includes six case studies of CSOs, stormwater, and agricultural runoff.

Moffa and Associates. (1999) Best Practices for Treatment of Wet Weather Flows. WERF Project No. 00-CTS-6. Retrieved January 16, 2002 from the World Wide Web: http://www.werf.org/research/search/

Kentucky CSO Demonstration Project to Evaluate Technology. WERF Progress Winter 2000. Retrieved January 16, 2002 from the World Wide Web: http://werf.rd.net/press/Winter00/

Ohio River Valley Water Sanitation Commission. Combined Sewer Overflow Studies. Retrieved January 15, 2002 from the World Wide Web: http://www.orsanco.org/watqual/rec/cso.htm

U.S. EPA. (2000) SSO Case Study: Fairfax County, Virginia CMOM Program. Retrieved January 15, 2002 from the World Wide Web: http://www.epa.gov/npdes/sso/virginia/

U.S. EPA. (2000) SSO Case Study: Oklahoma City Sewer Line Replacement Program. Retrieved January 15, 2002 from the World Wide Web: http://www.epa.gov/npdes/sso/oklahoma/

U.S. EPA. (1998) Environmental Technology Verification Program Wet Weather Flow Technologies Pilot. Retrieved January 16, 2002 from the World Wide Web: http://www.epa.gov/etv/09/09_main.htm

Ongoing Research

No research was identified as ongoing.

Biosolids Application

Recent Research

Arnold, K., J. Dunn, and J. Carpenter. (1994) Best Management Practices for Biosolids Land Application. University of Missouri Water Quality Initiative Publication WQ426. Retrieved January 2, 2002 from the World Wide Web: http://muextension.missouri.edu/xplor/envqual/wq0426.htm

AWWARF Internet Search of Water Resource Protection Research: 2000 (Search of USGS, USDA, USEPA, and foreign water research centers. Retrieved January 3, 2002 from the World Wide Web: http://www.awwarf.com/research/standardcontract.html

Barbour, M.T. and Tetra Tech, Inc. (In Press) Assessment of the Status, Usefulness and Resource Requirements for Implementation of Biocriteria for Water Quality Standards. WERF. Duration: Completed.

> The primary objective of this project is to help plan a future for the use of biocriteria in the water quality management process. The project will include conducting a survey and preparing a report. The survey will contact as many users and potential users of biocriteria as possible to collect information. The report will include summaries of various biocriteria currently used and there users. It will summarize how biocriteria have been developed and how much effort is necessary to assure that they are based on a good scientific foundation.

Bruggeman, A.C. and S. Mostaghimi. (1993) Sludge Application Effects on Runoff, Infiltration, and Water Quality. Water Resources Bulletin 29:15-26. Retrieved January 3, 2002 from the World Wide Web: http://www.nal.usda.gov/wqic/Bibliographies/eb9602.html)

Colorado State University. Best Management Practices for Manure Application. Colorado State University Soil Publications. Retrieved January 4, 2002 from the World Wide Web: http://www.colostate.edu/Depts/SoilCrop/extension/Soils/SoilPublications.html

Gilliam, J.W., D.R. Shaw, S.C. Whalen, and D.M. Miller. Utilization of Best Management Practices for the Treatment of Animal Waste, Sludge, and Herbicides. Water Resources Research Act Grant. Duration: July 1, 1996 to August 31, 1997.

> Results of this research will help refine current agricultural BMPs and further reduce the risk of contaminants from impacting water resources. More specifically, issues of the effectiveness of filter strips (natural and man-made) in removing contaminants from runoff will be refined; the development of practices that promote denitrification and provide the nitrogen requirement for cover crops will be defined; and the utilization of sludge as a soil amendment for pasture growth will be defined. Part of the proposed research is designed to determine effectiveness of various widths of both planted and naturally vegetated buffers to remove contaminants from runoff water from fields receiving animal waste. Another part of the proposal will evaluate the effect of varying

filter strips width on off-site movement of two widely used soil-applied herbicides. This portion of the study will also evaluate the off-site movement over time and runoff event.

University of Tennessee. Best Management Practices (BMPs) for Land Application of Biosolids. University of Tennessee Agricultural Extension Service and Tennessee Division of Water Pollution Control. Retrieved January 3, 2002 from the World Wide Web: http://www.utextension.utk.edu/spfiles/sp500.pdf

U.S. EPA. (1994) A Plain English Guide to the EPA Part 503 Biosolids Rule. 832/R-93/003. Retrieved January 4, 2002 from the World Wide Web: http://www.epa.gov/owm/bio/503pe/

U.S. EPA. (2000) Guide to Field Storage of Biosolids. 832/B-00/07. Retrieved January 4, 2002 from the World Wide Web: http://www.epa.gov/owm/bio/fsguide/index.htm

U.S. EPA. Technology Fact Sheets. Retrieved January 4, 2002 from the World Wide Web: http://www.epa.gov/owm/mtbfact.htm

WERF and M.E. Lang. National Manual of Good Practice for Biosolids. Project # 99-PUM-5T. Retrieved January 3, 2002 from the World Wide Web: http://www.werf.org/research/search/index.cfm?fuseaction=projectinfo&index=196&requesttimeout=600&_CFID=199110&CFTOKEN=4134549

WERF and Albert B. Pincince. Innovative Biosolids Management Techniques Assessment. Project #96-REM-1. Retrieved January 4, 2002 from the World Wide Web: http://www.werf.org/research/search/index.cfm?fuseaction=projectinfo&index=13&requesttimeout=600&CFID=199110&CFTOKEN=4134549

Wright, R.J., W.D. Kemper, P.D. Millner, J.F. Power, and R.F. Korcak (Editors). (1998) Agricultural Uses of Municipal, Animal, and Industrial Byproducts. U.S. Department of Agriculture, Agricultural Research Service, Conservation Research Report No. 44, 135 pp. Retrieved January 3, 2002 from the World Wide Web: http://www.ars.usda.gov/is/np/agbyproducts/agbycontents.htm

Ongoing Research

To Be Determined. Characterizing the Forms, Solubilities, Bioavailabilities, and Mineralization Rates of Phosphorus in Biosolids, Commercial Fertilizers and Animal Manures (Phase I). Duration: 2 years. WERF.

> Will provide information relative to phosphorus in biosolids as well as other nutrient rich products, and the biosolid/product-soil matrices that can be used to assist in the development of workable and environmentally sound phosphorus management plans.

To Be Determined. Develop Methods to Detect and Enumerate Human Parasites in Municipal Biosolids. Duration: 3 years. WERF.

> Will screen, identify, and select an appropriate surrogate human parasite(s) (in lieu of helminth ova), then develop protocols to recover, detect, and measure the selected surrogate organism(s) for municipal wastewater biosolids.

Injection Wells

Recent Research

Cox, D., P. Onsager, J. Thomson, R. Reinke, G. Gianinny, C. Vliss, J. Hughes, and M. Janowiak. (2001) San Juan Basin Ground Water Modeling Study: Ground Water – Surface Water Interactions Between Fruitland Coalbed Methane Development and Rivers. Ground Water Protection Research Foundation. Retrieved January 3, 2002 from the World Wide Web: http://www.gwpc.org/San_Juan_Basin_Modeling_Study/San_Juan_Basin_Modeling_Study.pdf

> This project modeled surface water and ground water interactions associated with coal bed methane (CBM) development in the northern San Juan Basin of CO. Ground water production from coalbed aquifers is required for recovering CBM. By pumping water, the pressure in the CBM reservoir is reduced and methane then desorbs from the coal and flows through the natural cleat system to the pumping wells. This project was designed to quantify the maximum surface water depletion that may occur as a result of CBM development in the Fruitland Formation.

U.S. EPA, Office of Ground Water and Drinking Water. (1999) The Class V Underground Injection Control Study. EPA/816-R-99-014. Retrieved January 18, 2002, from the World Wide Web: http://www.epa.gov/safewater/uic/classv/volume1.pdf

U.S. EPA, Office of Ground Water and Drinking Water. (2001) Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells. EPA 816-R-01-007.

Ongoing Research

No research was identified as ongoing.

Abandoned Wells

Recent Research

Aller, L. (1984) Methods for Determining the Location of Abandoned Wells. Final report. National Water Well Association, Worthington, Ohio; Robert S. Kerr Environmental Research Lab., Ada, Oklahoma. Report No.: EPA/600/2-83-123.

American Society for Testing and Materials. (2001) Standard Guide for Locating Abandoned Wells. Guide D6285-99. Retrieved December 7, 2001 from the World Wide Web: http://enterprise.astm.org/PAGES/D6285.htm

> This guide provides an approach to selecting and implementing a program to locate abandoned wells. Methods include records reviews, airborne and space-based photographic methods, and geophysical methods.

Jianghai Xia. (2001a) Feasibility Study on Using the Electromagnetic Method to Locate Abandoned Brine Wells in Hutchinson, Kansas. Kansas Geological Survey Open File Report 2001-10. Retrieved December 7, 2001 from the World Wide Web: http://www.kgs.ukans.edu/Geophysics/OFR/2001/10/index.html

> An electromagnetic (EM) survey was conducted in Hutchinson, Kansas, as a part of effort to locate abandoned brine wells. EM anomalies identified in the field were verified immediately. Although no brine well was found on the proposed sites, the EM survey was successful from a geophysical point of view because it showed promise and effectiveness in locating the brine wells.

Jianghai Xia. (2001b) Using the Electromagnetic Method to Locate Abandoned Brine Wells in Hutchinson, Kansas. Kansas Geological Survey Open File Report 2001-17. Retrieved December 7, 2001 from the World Wide Web: http://www.kgs.ukans.edu/Geophysics/OFR/2001/17/

> An electromagnetic (EM) survey with a GEM-2, an electromagnetic instrument, was conducted in Hutchinson, Kansas, as a part of effort to locate abandoned brine wells. EM results successfully located one uncapped abandoned brine well, 4 inches in diameter and buried at a depth of 5 ft. This survey result indicates the potential investigation depth with a GEM-2 would be as deep as 20 ft in locating abandoned wells in the Hutchinson area. The survey also demonstrated the importance of acquiring target signals in interpreting anomalies. The EM survey in Hutchinson proved to be successful and effective in locating the abandoned brine wells.

Kubichekl, R., J. Cupal, W. Iverson, S. Choi, and M. Morris. (1997) Identifying Ground Water Threats from Improperly Abandoned Boreholes. Electrical Engineering Department, University of Wyoming, Laramie, Wyoming. Retrieved December 6, 2001 from the World Wide Web: http://www.engg.ksu.edu/HSRC/97abstracts/doc29.html

> The University of Wyoming investigated the use of acoustical techniques to determine the status of plugged and abandoned wells. During the summer of 1996, seven wells were acoustically tested. The best results were seen on tests of an unplugged water well, where strong reflections were seen from the 3000-foot-deep well bottom. Acoustic records from the plugged wells have been more challenging to interpret. If successful, the technique could be used to determine which abandoned wells require mitigation.

USGS. (1995) Magnetic Surveys for Locating Abandoned Wells. Fact Sheet 163-95. Retrieved December 10, 2001 from the World Wide Web: http://greenwood.cr.usgs.gov/public/fact-sheets/fs-0163-95/FS163-95.html

> Carefully designed ground magnetic or aeromagnetic surveys can be used to locate abandoned wells by mapping the magnetic disturbances produced by their steel well casings. The USGS can conduct, process, and interpret such surveys, or it can aid in the design and monitoring of contracts for such surveys.

U.S. Minerals Management Service. (No Date) Using Satellite Radar Imagery to Detect Leaking Abandoned Wells on the U.S. OCS. Project Number 355. Available on the World Wide Web: http://www.mms.gov/tarprojects/355.htm

> This project uses satellite radar imagery to detect if there are leaking abandoned wells. The methodology will be tested in Phase I. An optional Phase 2 of the project will check the Gulf of Mexico Region.

Wilson, C. R., G. Tsoflias, M. Bartelmann, and J. Phillips. (1997) A High Precision Aeromagnetic Survey near the Glen Hummel Field in Texas; Identification of Cultural and Sedimentary Anomaly Sources. The Leading Edge. Retrieved January 21, 2002 from the World Wide Web: http://edge-online.org/pdf/tle1601r0037.pdf

> This paper presents a case study of a high resolution aeromagnetic survey near the Glen Hummel oil field. The survey was originally flown to support a study of aeromagnetic methods for environmental hazard detection, but it provides an opportunity to investigate various problems that arise when analyzing low level total field magnetic anomalies in an area of petroleum production.

Zwilling, Dan. (No Date) Well Sealing Program. Minnesota Department of Natural Resources. Retrieved January 21, 2002 from the World Wide Web: http://www.dnr.state.mn.us/waters/programs/gw_section/wellseal/

Ongoing Research

No research was identified as ongoing.

Water Conservation, Reuse, and Recycling

Recent Research

Al-Kaisi, Mahdi. (2000) Conservation Buffers and Water Quality. *In*: Integrated Crop Management, Department of Entomology, Iowa State University. Retrieved January 10, 2002 from the World Wide Web: http://www.ent.iastate.edu/ipm/icm/2000/6-12-2000/consbuffers.html

> Conservation buffers are an effective and cost-efficient best management practice that can be used to improve water quality. They can be different-sized areas or strips in permanent vegetation that minimize soil erosion by reducing surface runoff. Conservation buffers also can trap and degrade a portion of runoff adsorbed to sediments or dissolved in water; they are seldom effective in trapping all pesticides in runoff. Conservation buffers can be used along with other best management practices to protect water quality.

American Water Works Association (AWWA), Research Foundation. (1997) Long-term Effects of Conservation Rates. AWWA Research Foundation, Denver, Colorado.

American Water Works Association and Water Environment Federation. (1998) Using Reclaimed Water to Augment Potable Water Resources. 357 pp.

Arber, R. (1991) Wastewater Reuse Thoroughly Examined. Water/Engineering & Management 138(5). National Small Flows Clearinghouse.

> Many municipalities are adopting programs to address water reuse. Land application, indirect potable reuse, and direct potable reuse are options available for reuse of wastewater. This article discusses these three options and reasons why direct potable reuse has not been implemented.

Bhatia, R., R. Cestti, and J. Winpenny. (1995) Water Conservation and Reallocation: Best Practice Cases In Improving Economic Efficiency and Environmental Quality. World Bank, Washington, D.C. A World Bank-ODI Joint Study (Referenced in OAS, 1997).

Bosch, D.J. and B.B. Ross. (1990) Improving Irrigation Schedules to Increase Returns and Reduce Water Use in Humid Regions. Journal of Soil and Water Conservation 15(4):485-488.

Crook, J. and R. Bastian. (1992) EPA Guidelines Developed for Water Reuse. Water Environment & Technology 4(8). National Small Flows Clearinghouse.

An updating and expansion of the EPA GUIDELINES FOR WATER REUSE is reviewed. The guidelines are meant to encourage states without regulations or guidelines for water reuse to consider this option. Information is provided about evaluating requirements and reuse benefits. Key issues covered are evaluation of water reclamation and reuse opportunities, assessment of costs and benefits of reuse alternatives, planning and implementing water reuse systems. Also discussed are major technology and non-technology isses form the experiences of regulatory agencies, utility districts, municipalities, consulting engineers and reclaimed water users.

Crook, J. (1993) Water Reuse in the U.S. National Small Flows Clearinghouse.

This report focuses on current and future issues in water reuse. A brief historical perspective on the reuse of water in the U.S is provided as well as current methods used. Current techniques include irrigation for agriculture or landscaping, industrial uses such as cooling or boiler process waters, dual potable/non-potable water systems, recreational uses and habitat restoration or enhancement. All areas are explored concisely and many examples of successful systems are given with attention to the flowrates and major water quality parameters (BOD, COD, TSS). Also discussed are guidelines and regulatory issues involved including a brief summary of EPA's 1992 "Guidelines for Water Reuse" with the major points emphasized.

Cuthbert, W.R. (1989) Effectiveness of Conservation Oriented Water Rates in Tucson. Journal of the American Water Works Association 81(3): 65-73.

Daniel, T.C., D.H. Mueller, B.J. Andraski, and R.E. Springman. (1988) Effect of Tillage on Erosion, Runoff and Runoff Water Quality. University of Wisconsin, Cooperative Extension Service (G3432) 5 pp. *In* subseries: Farm Management & Water Quality, Madison, Wisconsin.

Dillaha, T.A. (1989) Water Quality Impacts of Vegetative Filter Strips. American Society of Agricultural Engineers. Paper No. 89-2043, 9 pp.

Logan, T.J., et al. (Editors). (1987) Effects of Conservation Tillage on Groundwater Quality : Nitrates and Pesticides. pp. 271-276.

Elsner, M. and M. Paret. (1993) Reclaimed Water Perspectives. Water Environment and Technology 5(2). National Small Flows Clearinghouse.

> This article is an investigative study on the economic feasability of water reuse in the state of Florida. Florida's five water management districts surveyed major users of reclaimed water in the state with questionnaires. The survey reports on reclaimed water consumption, service arrangements and fees, and construction costs. These regulations require wastewater treatment facility owners, water treatment plant owners, and applicants for consumptive water-use permits to investigate the economic feasibility of reuse as a disposal method; as a type of conservation, and as a source of water, respectively.

Federal Energy Management Program (FEMP). Retrieved from the World Wide Web: http://www.eren.doe.gov/femp/techassist/best_practices.html

Kanwar, R.S., J.L. Baker, and D.G. Baker. (1987) Tillage and N-fertilizer Management Effects on Groundwater Quality. American Society of Agricultural Engineers. Fiche No. 87-2077, 18 pp.

Koerkle, E.H. (1992) Effects of Nutrient Management on Surface Water Quality in a Small Watershed in Pennsylvania. *In* Proceedings: The National RCWP Symposium: 10 Years of Controlling Agricultural Nonpoint Source Pollution, the RCWP Experience. September 13-17, 1992, Orlando, Florida, pp. 193-207.

Kromm, D.E. and S.E. White. (1990) Adoption of Water Saving Practices by Irrigation in High Plains. Water Resources Bulletin 26(6):999-1012.

Logan, T.J. (1987) An Assessment of Great Lakes Tillage Practices and Their Potential Impact on Water Quality. Lewis Publishers.

Martin, W.E. and S. Kulakowski. (1991) Water Price as a Policy Variable in Managing Urban Water Uses: Tucson, Arizona. Water Resources Research 27(2):157-166.

McPherson, B.F. and R. Halley. (1996) The South Florida Environment- A Region Under Stress. U.S. Geological Survey Circular 1134. Retrieved January 10, 2002 from the World Wide Web:
http://sofia.usgs.gov/publications/circular/1134/Circular1134.pdf
http://sofia.usgs.gov/publications/circular/1134/wes/deg.html

> In past years, the prime threat to ground-water quality in south Florida has been that of seawater intrusion in coastal areas and near heavily pumped municipal wells. In recent years, however, seawater intrusion generally has been controlled by providing sufficient freshwater so that adequate high-water levels are maintained near the coast

McTernan, W.F., B.L. Weand, and T.J. Grizzard. (1987) Evaluation of Management Practices to Control Agricultural Pollutants. Water Resources Bulletin 23(4):691-700.

Michelsen, Ari M. (1998) Effectiveness of Residential Water Conservation Price and Nonprice Programs. AWWA, Denver, Colorado.

Mostaghimi, Saied. (1988) Tillage Effects on Runoff Water Quality from Sludge-amended Soils. Virginia Water Resources Research Center, U.S. Geological Survey, Branch of Water Institute Programs, Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University. XI, 81pp.

Negri, Donald H. (1989) Water Conservation Through Irrigation Technology. U.S. Department of Agriculture, Washington, DC.

Organization of American States (OAS). (1997) Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean. Prepared by the Unit of Sustainable Development and Environment of the General Secretariat of the OAS as part of the joint United Nations Environment Programme (UNEP), Water Branch and International Environmental Technology Centre (IETC). Retrieved January 10, 2002 from the World Wide Web: http://www.oas.org/usde/publications/unit/oea59e/begin.htm

Pearson, F.H. (1993) Study Documents Water Savings with Ultra Low Flush Toilets. Small Flows 7(2):8-9, 11.

Renken, R.A. (1998) U.S. Geolgical Survey Hydrologic Atlas 730-F. Retrieved January 11, 2002 from the World Wide Web: http://capp.water.usgs.gov/gwa/pub/ch_f/F-text.ascii

> The States of Arkansas, Louisiana, and Mississippi, which are located adjacent to each other and north of the Gulf of Mexico, compose Segment 5 of this Atlas. Describes how decreased water levels result in increased TDS and salinity.

Ritter, W.F., A.E.M. Chirnside, and R.W. Lake. (1988) Best Management Practices Impacts on Water Quality in the Appoquinimink Watershed. American Society of Agricultural Engineers. Fiche No. 88-2034, 24 pp.

Smith, M. (1992) Vegetative Filter Strips for Improved Surface Water Quality. Iowa State University, Cooperative Extension Service. 1507, 4 pp.

U.S. EPA. (1995) Cleaner Water Through Conservation. Report No. EPA-841/B-95-002, Washington, DC.

U.S. EPA. (1993) Xeriscape Landscaping: Preventing Pollution and Using Resources Efficiently. EPA 840/B-93-001

U.S. EPA. (1992) Manual: Guidelines for Water Reuse. Report No. EPA-625/R-92-104, Washington, DC.

Ongoing Research

Aziz, A., S. Warren, and W. Robarge. Reuse of Wastewater from Septic Systems. Water Resources Research Grant Proposal. Duration: 03/01-02/02 http://water.usgs.gov/wrri/01grants/NC801.pdf

> Limited research has been conducted on the use of gray water (wastewater generated from a dwelling excluding toilet, kitchen sink/garbage disposal, and dishwashing machine) for irrigation. Gray water is being considered for irrigating lawns and gardens in Arizona and California where water shortages are common. This proposal intends to determine the feasibility of on-site use of untreated wastewater from kitchen and laundry facilities for irrigating home landscapes. This general objective will be addressed by determining the characteristics of wastewater from kitchen and laundry facilities from typical residential dwellings and the subsequent effect of this wastewater on growth, appearance, and survival of ornamental plants.

Renken, Robert A. Synthesis on the Impact of 20th Century Water-Management and Land-Use Practices on the Coastal Hydrology of Southeastern Florida. Abstract retrieved from the World Wide Web: http://sofia.usgs.gov/projects/impact_auc/synthabgeer00.html

> Saltwater intrusion in the surficial aquifer system is a direct consequence of water-management practices, concurrent agricultural and urban development, and natural drought conditions. The objectives of this synthesis are to: (1) provide a temporal and spatial overview of coastal saltwater intrusion in southeastern Florida; (2) identify the principal factors that control the extent of saltwater intrusion; (3) evaluate long-term trends in ground-water withdrawal rates, ground-water-level change, rainfall, and increases in chloride concentration; and (4) illustrate causal relations between the position of the saltwater interface, water-management practices, and the expansion of agricultural and urban areas.

Rockwood, Donald L. and Gillian R. Alker. Modeling the Fate of Reclaimed Water Constituents after Application to Tree Crops. State Water Resources Research Grant Proposal. Project Duration: March 2000 to February 2001. Abstract retrieved from the World Wide Web: http://water.usgs.gov/wrri/00grants/FLcrops.html

> The objective of the research is to develop a model which will predict the fate and transport of nitrogen, water and chloride in reclaimed water after application to SRIC crops. Crop demand will be used to drive irrigation scheduling which may be utilized by growers and reclaimed water facilities to both minimize the risk associated with nitrate leaching to groundwater and to maximize crop production.

Thiem, L.T., V.C. Rose, and S. Barnett. Realistic Restoration of Streamflow in the Chipuxet Basin. State Water Resources Research Grant Proposal. Project Duration: March 1, 2000 to April 30, 2001. University of Rhode Island, Kingston. Abstract retrieved from the World Wide Web: http://water.usgs.gov/wrri/00grants/RIchipuxet.html

> This project will first quantify water demands on the Chipuxet Aquifer and classify them as to use. Once the major sources of water demands are quantified the next part of the study will be initiated. An evaluation of these water demands will be conducted to determine the feasibility of returning the water to the aquifer. Special attention will be given to the elimination of the exporting of water out of the Chipuxet Basin. One potential option would be to separate the wastewater that is used by URI into Grey Water (from showers and washing in the URI athletic and housing complexes) and use this water for irrigation. Black water (sewage) currently being pumped to the South Kingstown Wastewater Treatment Facility in Narragansett, RI. could be treated by conventional processes (activated sludge) or by new technology (membrane processes). This treated water could be returned to the aquifer by irrigation or by direct injection. The results from this proposal can serve as a pilot program for other water utilities that rely on stressed aquifers.

Water Testing Will Measure Farming Practices Effectiveness. Abstract retrieved from the World Wide Web: http://www.ctic.purdue.edu/Core4/MAX/1997/Page8b.html

> This was the first year of a five-year project in the watershed jointly sponsored by the Natural Resources Conservation Service, Sangamon County Sod and Water Conservation District, Illinois Water Survey and University of Illinois Cooperative Extension Service. These, in turn, will be the areas where filter strips and conversion to no-till and conservation tillage will be emphasized. Timing of herbicide application will also be studied, such as the runoff effect of chemicals applied pre-emerge versus post-emerge.

Aquifer Recharge, Aquifer Storage and Recovery, and Aquifer Remediation

Recent Research

Bouwer, H. (1991) Role of Groundwater Recharge in Treatment and Storage of Wastewater for Reuse. Water Science Technology 24 (9). Small Flows Clearinghouse.

> Where hydrogeologic conditions permit groundwater recharge with surface infiltration facilities, considerable water quality improvement is obtained by the movement of the wastewater through the soil, vadose zone, and aquifer. The resulting soil-aquifer treatment costs are less than 40% of the costs of equivalent in-plant treatment. Soil-aquifer treatment systems also are simple and robust, offer storage of the water to adsorb

differences between supply and demand, and enhance the aesthetics of potable reuse of wastewater. Hence, they can play an important role in wastewater reuse.

Dickenson, J.M. (1997) ASR and Ground Water Basin Management. Proceedings of AWRA Symposium: Conjuctive Use of Water Resources: Aquifer Storage and Recovery. Long Beach, California. American Water Resources Association, Harndon, Virginia, pp. 155-162.

Gildea, M.L., W.L. Bratton, and L.D. Stewart. (1997) Demonstration of Steam Injection as an Enhanced Source Removal Technology for Aquifer Restoration. Applied Research Associates, Inc., South Royalton, Vermont, New England Division. 335 pp.

Steam injection combined with groundwater pumping and soil vapor extraction was demonstrated at Operable Unit One (OU-1), Hill AFB, Utah. The purposes of the research were to increase understanding of the technology and evaluate its effectiveness for cleanup of non-aqueous phase liquids (NAPLs). The results will be included in an evaluation of various technologies for potential inclusion in the OU-1 Record of Decision.

Ma, L. and Spalding, R.F. (1997) Effects of Artificial Recharge on Ground Water Quality and Aquifer Storage Recovery. Journal of the American Water Resources Association 33(3):561-572.

Ground water nitrate contamination and water level decline are common concern in Nebraska. Effects of artificial recharge on ground water quality and aquifer storage recovery (ASR) were studied with spreading basins constructed in th e highly agricultural region of the Central Platte, Nebraska. A total of 1.10 million m3 of Platte River water recharged the aquifer through 5000 m2 of the recharge basins during 1992, 1993, and 1994. This is equivalent to the quantity needed to completely displace the ground water beneath 34 ha of the local primary aquifer with 13 m thickness and 0.26 porosity. Ground water atrazine concentrations at the site decreased from 2 to 0.2 mg L-1 due to recharge. Both NO3-N and atrazine contamination dramatically improved from concentrations exceeding the maximum contaminant levels to those of drinking water quality. The water table at the site rose rapidly in response to recharge during the early stage then leveled off as infiltration rates declined.

Miller, R.R. (1996a) Horizontal Wells. Ground-Water Remediation Technologies Analysis Center, Technology Overview Report TO-96-02.

Heterogeneous soils may cause channeling (preferential movement of a fluid - liquid or gas - through high conductivity layers and potentially away from the area of contamination).

Miller, R.R. (1996b) Air Sparging. Ground-Water Remediation Technologies Analysis Center, Technology Overview Report TO-96-04.

Pinholster, G. (1995) Drinking Recycled Wastewater: Can Groundwater Recharge Safely Address the Drinking-water Needs of Rapidly Growing Urban Areas. Environmental Science Technology 29:4 174A-179A.

Pitt, W.A.J. and S. Magenheimer. (1997) ASR Technology: Avoidance and Solutions to Aquifer Clogging Problems. Proceedings of the AWRA Symposium, Conjunctive Use of Water Resources: ASR, Long Beach, California. American Water Resources Association, Herndon, Virginia. pp. 251-260.

Pyne, R.D.G. (1996) Aquifer Storage Recovery of Drinking Water. University of North Carolina, AWWARF. Retrieved January 10, 2002 from the World Wide Web: http://www.awwarf.com/exsums/90689.htm

> This project was conducted to evaluate, under more controlled conditions, whether DBP reduction occurs and to assess the probable causes. Additional studies were conducted to evaluate well clogging relationships and to develop a hydrogeologic computer model for predicting the fate of conservative water quality constituents and also DBPs during ASR storage.

Pyne, R.D.G. (1995) Ground Water Recharge and Wells: A Guide to Aquifer Storage and Recovery. Lewis Publishers, Boca Raton, Florida.

Hayes, K.F., K.R. Srivivasan, J. Devgun, and S. Weber. Remediation of Contaminated Aquifers with Surfactants: Effect of Surfactant Sorption and Desorption. DOE Office of Technology and Development. Retrieved January 4, 2002 from the World Wide Web: http://www.cmst.org/OTD/tech_summs/IIA/EPA_HSRC/RemCntAqif.html

> Surfactants are being actively investigated as promising agents for remediation of contaminated aquifers. The goal of this project is to ultimately come up with guidance for application to actual groundwater remediation schemes.

Shea-Albin, V. (1997) Summary of info from the Report to Congress on the High Plains Aquifer Project. Prepared by U.S. EPA to be part of the preamble. U.S. EPA Region 8, Denver, Colorado.

Soliman, M., N. El-Din, and N.A. Hassan. (1995) Remediation of Contaminated Aquifers With Reclaimed Sewage Water. National Small Flows Clearinghouse. August 14-16 Issue.

> Sewage water lagoons were located on high ground of the area recharging contaminated water in the aquifer. Since the groundwater in this area is used for drinking purposes, it

was decided to treat the sewage water recharging the aquifer for health and beneficial purposes. In this paper a solution to the problem is presented using an injection well recharging good quality water into the aquifer. A pumping well located at a distance downstream is used to pump the contaminated water out of the aquifer. A three dimensional solute transport model was developed to study concentration distribution with remediation time in the contaminated zone.

Van Beek, C.G.E.M. (1986) Clogging of Discharge Wells in the Netherlands II: Control and Prevention. *In*: International Symposium on Biofouled Aquifers: Prevention and Restoration. American Water Works Association, Denver, Colorado, pp. 43-56.

Vandergrift, G.F., D.T. Reed, and I.R. Tasker (Editors). (1992) Environmental Remediation: Removing Organic and Metal Ion Pollutants. American Chemical Society Symposium Series 509. Retrieved January 10, 2002 from the World Wide Web: http://www.oup-usa.org/isbn/084122479X.html

Discusses current applications and new developments in separation science for the remediation of contaminated groundwater and soil. Examines waste treatment and waste avoidance technologies and the applications of separation science to waste minimization and preconcentration. Presents fundamental research for developing new technologies in the remediation of contaminated aquifers and surface and subsurface media. Offers insights into measuring the depth of problems and the effectiveness of treatment.

Vivoni, E.R. (2000) Distributed Aquifer Recharge Enhancements in Arid Zones. Massachusetts Institute of Technology. Retrieved January 31, 2002 from the World Wide Web: http://web.mit.edu/vivoni/www/aridzone.html

This paper explores the possibility of enjancing natural aquifer recharge by implementing a variant to time tested hydrologic technologies used for centuries in various arid watersheds. The ground water model, MODFLOW, is used to simulate an idealized catchment where a component of the Branched Aquifer Recharge System (BARS) have been suitably modeled.

Wang, J.C., J.R. Booker, and J.P. Carter. (1998) Analysis of the Remediation of a Contaminated Aquifer by a Multi-Well System. Dept. of Civil Engineering, Sydney University, Australia. Report No. RR-R777.

This paper presents a study of the remediation of a contaminated aquifer of uniform thickness by multi-well systems, which include both discharge wells and recharge wells. These investigations show that an appropriately designed pump and treat system (PAT) can have a significant effect on the decontamination of a polluted aquifer and can preclude the further spreading of a contaminant plume. However, if the system is not designed appropriately, it may cause a further serious spreading of the contamination.

This possibility is illustrated by the examples presented in the paper, which highlight the need for care in the design of remediation strategies.

Ziegler, A.C., T.J. Trombley, G.T. Blain, L.J. Klein, T.A. Pajor, V.A. and Strasser. (1997) Are Total Recoverable Analyses Necessary for Monitoring Water Quality in Recharge Studies? *In:* Water Quality Technology Conference, Denver, Colorado. Proceedings: American Water Works Association, compact disk.

During 1995 and 1996, water-quality samples were collected from the Little Arkansas River and adjoining *Equus* Beds aquifer to determine if information on total recoverable concentrations of chemical constituents is necessary to monitor potential effects of surface water recharged through infiltration basins to the aquifer.

Ziegler, A.C., V.G. Christensen, and H.C. Ross. (1999) Baseline Water Quality and Preliminary Effects of Artificial Recharge on Ground Water, South-Central Kansas, 1995-98. USGS Water Investigations Report 99-4250.

It may be possible to decrease monitoring frequency at the Halstead site because water-quality changes in receiving ground water at this site are very gradual. However, more information is needed at the Sedgwick site. Real-time water-quality monitoring could improve the effectiveness of the current monitoring program used by the *Equus* Beds Ground-Water Recharge Demonstration Project. To investigate the feasibility of artificial recharge as a method of meeting future water-supply needs and to protect the *Equus* Beds aquifer from saltwater intrusion from natural and anthropogenic sources to the west, the *Equus* Beds Ground-Water Recharge Demonstration Project was begun in 1995.

Ongoing Research

Hanson, Randall T. (Project Chief). Analysis of the Subsidence and Water-Management Issues of the Santa Clara Valley, California. USGS. Project Duration: April 1999 through September 2002. Retrieved from the World Wide Web: http://ca.water.usgs.gov/projects00/ca554.html

The objectives of the proposed study are to develop a management tool that incorporates new geohydrologic and geomechanical data that helps further development of ground-water while minimizing of additional subsidence. These data in combination with an upgraded and updated 3-D ground-water/ surface-water flow model would provide the tools to help answer the following questions: 1) Is subsidence still occurring and, if so, where and how much? 2) How much of the subsidence is elastic (recoverable) and how much is inelastic (nonrecoverable)? 3) What are the sources, movement, and age of ground water in the Santa Clara Valley? What are the renewable resource for aquifer system and what portions of aquifer system is being mined? 4) What are the most efficient strategies for controlling subsidence? 5) How can pumpage be optimally distributed with depth and rate to minimize the potential for permanent subsidence? 6) How can artificial-recharge facilities (aquifer storage and recovery) be optimally operated to maximize recharge, minimize overdraft pumpage, minimize additional loading from perched aquifers, and minimize spreading of poor quality waters? 7) How will variability in climate (especially drought conditions) and the related availability of natural and artificial recharge affect the distribution of subsidence? In summary: the objective of this study is to refine the groundwater management tool used by the Dsitrict that incorporates new geohydrologic data, new geomechnaical data, and new modeling techniques into the existing SCVWD regional flow model.

Idaho Department of Water Resources. (1999) Feasibility of Large-Scale Managed Recharge of the Eastern Snake Plain Aquifer System. Retrieved from the World Wide Web: http://www.idwr.state.id.us/recharge/

This report describes the potential of a managed recharge program to enhance conjunctive management of water resources in the Eastern Snake River Plain (ESRP). Large-scale managed recharge is evaluated in the context of institutional, environmental, hydrologic, and engineering factors that influence and characterize the feasibility of operational implementation. Restoring ground-water levels in the central part of the Plain and spring discharges in the Thousand Springs and American Falls reaches of the Snake River are two key hydrologic objectives of large-scale managed recharge in the ESRP.

Ground Water Recharge and Conservation. Retrieved from the World Wide Web: http://www.mercedid.org/recharg.htm

Merced Water Supply Plan: Engineers have begun a pilot project involving intentional ground water recharge, in which at least three test basins will be built and studied. If experiment is successful, the Merced Water Supply Plan would fund the construction of other recharge basins throughout eastern Merced County, in an effort to artificially recharge the ground water supply.

McCarty, P.L., J. Devgun, and S.C. Weber. In-Situ Bioremediation of Chlorinated Aliphatic Compounds by Phenol Utilizing Bacteria. DOE Office of Technology and Development. Retrieved from the World Wide Web: http://www.cmst.org/OTD/tech_summs/IIA/EPA_HSRC/BioremChlor.html

The goal of this project is to evaluate, in the field, the rate and extent of degradation of chlorinated aliphatic compounds through cometabolism using phenol as a primary substrate

Water District and Lawrence Livermore National Laboratory. Predicting Water Quality Changes From Artificial Recharge Sources to Nearby Wellfields [#486]Alameda County (California). Research partner: Alameda County Water District. AAWARF. To be completed in 2002.

> Will quantify water quality changes that take place during transit from surface water recharge points to groundwater production wells supplying drinking water. Will use state-of-the-art isotope tracer techniques combined with low-level organic and inorganic analyses and pathogen monitoring.

Centre for Groundwater Studies and CSIRO (Australia) Land and Water. Water Quality Improvements During Aquifer Storage and Recovery [#2618]. AWWARF. To be completed in 2003.

> Will characterize chemical, physical, and biological processes that contribute to water quality improvements during aquifer storage and recovery (ASR) and will develop a method to estimate these water quality improvements.

Effective Contingency Planning

Detection Methodologies

Recent Research

Abbaszadegan, Morteza. (1998) Application of PCR Technologies for Virus Detection in Groundwater. American Water Works Service Company, AWWARF, and U.S. EPA.

> Evaluates the application of polymerase-chain-reaction technology for virus detection in groundwater. Will investigate the occurrence of enteroviruses, hepatitis A virus, Norwalk virus, and rotavirus in 250 groundwater sources.

Abbaszadegan, M., P.W. Stewart, M.W. LeChevallier, Rosen, Jeffery S. and C.P. Gerba. (1999) Occurrence of viruses in ground water in the United States. American Water Works Association Research Foundation. Denver, CO, p. 162.

> Estimates national pathogen and indicator occurrence. Sampled 448 wells in 35 states. Indicators monitored were somatic coliphage, host *E. coli* C, *E. coli* C-3000, Male-sp. coliphage, host Salmonella WG-49, total coliform, enterococci, and *C. perfringens*. Pathogenic viruses monitored through cell culture and PCR were enterovirus, rotavirus, hepatitis A virus, and Norwalk virus.

AWWA. (2002) Design of Early Warning and Predictive Source Water Monitoring Systems.

Includes discussions of emerging technologies such as electronic "noses" for detecting odors, DNA chips, cytometry, immunoassay, PCR, electrochemiluminescense, bioluminescense, ribotyping, and immunomagnetic separation for rapid detection of pathogens. Most of these methods are currently under development by the US military.

Azcona-Olivera, Juan I. and Bennett G. Smith. (2001) An Efficient Immunomagnetic Capture System for *Enterococcus faecalis* and *Enterococcus faecium.* Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

Enterococci detection is one of the two approved procedures by EPA used for the assessment of the microbiological quality of recreational waters. The action levels established by the EPA for *enterococci* are 35 per 100 ml in marine recreational waters and 33 per 100 ml in fresh water. Turn-around time of the method is over 24 hr, and thus there is a clear need to reduce that time to allow a faster and reliable assessment of the safety/quality of the waters. The most abundant and prevalent species among the fecal *enterococci* (>90%) are *E. faecalis* and *E. faecium*. Our objective is to devise an efficient bacterial capture/concentration system in conjunction with a rapid detection method that will make possible the assessment of very low levels of fecal *enterococci* within a working day. In the first phase of our project described in this paper our objectives have been twofold (1) the procurement and/or production of antibodies able to capture efficiently the above mentioned microorganisms and (2) the evaluation of various tagging alternatives (nucleic acid based generic dyes, specific antibody fluorochrome-conjugates, etc) for the detection of *enterococci* with the RBD2000, a specialized flow cytometer designed for bacterial detection. This initial part of the project has been done in clean samples spiked with various bacterial loads. The next phase of our project is to test the reagents produced and the methods developed in real samples, being our final goal the full development and validation of a flow cytometry based method that will enable the detection and enumeration of low levels of fecal *enterococci* in recreational waters in less than 8 hr.

Baggelaar, P.K. (Completed) Methods for Obtaining Information about Surface Water Quality, Within the Scope of Drinking Water Production: Situation, Trends, Disasters. Kiwa Research & Consultancy, Kiwa, Netherlands

Obtaining relevant information quickly about the situation and dynamics of the quality of the raw water is now possible using the methods described within the scope of this research project. The methods offer companies that use surface water as raw water better possibilities for safeguarding drinking water supplies.

Banks, W.S.L., C.A. Klohe, D.A. Battigelli. (2001) Occurrence and distribution of enteric viruses in shallow ground water and factors affecting well vulnerability to microbiological contamination in Worcester and Wicomico Counties, Maryland. USGS Water-Resources Investigations Report 01-4147.

Estimates national indicator and pathogen occurrence. Sampled 27 wells from Maryland coastal plain and 91wells from Maryland Piedmont fractured bedrock. Results from Piedmont wells are not available. Indicators monitored were somatic coliphage, male specific coliphage, *Bacterioides fragilis* phage, *C. perfringens*, total coliform, and enterococci. Enteric virus was monitored by cell culture and RT-PCR.

Battigelli, D.A. (1999) Monitoring ground waters in Wisconsin, Minnesota, and Maryland for enteric viruses and candidate viral indicators. Unpublished report, February 23, 1999.

Estimates national indicator and pathogen occurrence. Sampled 76 wells from Minnesota, 25 from Wisconsin, 27 from Maryland coastal plain, 91 from Maryland Piedmont fractured bedrock. Results from Piedmont wells are not available. Indicators monitored were somatic coliphage, male specific coliphage, *Bacterioides fragilis* phage, *C. perfringens*, total coliform, enterococci, and *E. coli*. Enteric virus was monitored by cell culture and RT-PRC.

Battigelli, D.A., M. Borchardt, S.K. Spencer, M.M. Marshall, and J. Moffeft. (2001) Development of Methods for the Detection of Microsporldia in Model and Natural Waters. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

The microsporidia belong to a group of obligate intracellular parasites which are common to a variety of animal hosts. The environmentally resilient spores associated with human infection are typically -2 [tm in length], rendering them difficult to visualize by direct microscopic methods. Little is known about their fate and ecology in the aquatic environment but since species of microsporidia are ubiquitous in natural waters, some of which are infectious to humans, this group has significant implications for the water industry. Surface waters are common environmental sources of microsporidia (Avery and Undeen, 1987). Approximately 143 genera representing over 1200 different species are known to exist and infect nearly every known vertebrate and invertebrate (Bryan, 1995; Cali and Owen, 1992; Sparfel et al., 1997). The first report of microsporidiosis infection in humans was reported in 1959 (Garcia and Bruckner, 1997); however, at least 12 species in 5 different genera are known to affect humans (Didier et aL, 1998). Most human infections are found in association with late stages of HIV infections and produce a variety of systemic and non-systemic diseases (Didier et al, 1998; Garcia and Bruckner, 1997; Kotler and Orenstein, 1994; Kotler and Orenstein, 1998) but reports of infection in individuals suffering from liver disease (Furuya et aL, 1995) may suggest that the endemic level of disease is underestimated by current reporting methods.

Baudart, J., A. Olaizola, P. Laurent, J. Coallier, and M. Prevost. (2001) New Rapid Methods to Track Diluted *Enterobacteriaceae* Cells in Drinking Waters. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

Drinking water quality assessment involves the specific, sensitive and rapid detection of bacterial indicators in water samples. This work assesses the sensitivity of a new FISH method, combined with a physiological assay for direct enumeration at single-cell level of highly diluted viable *Enterobacteriaceae* cells in drinking waters. The approach (DVC-FISH) was completed by the use of a new direct detection device, the solid-phase laser cytometer (ScanRDI). The DVCFISH method combined with ScanRDI detection make it possibe to detect as little as one targeted cell in approximately 108 no targeted cells plotted on a membrane. This new approach as applied to a drinking water distribution system was investigated.

Bischoff, M., A.M. Hiar, and R.F. Turco. (1996) Evaluation of Nitrate Analysis Using Test Strips: Comparison with Two Analytical Laboratory Methods. Commun. Soil Sci. Plant Anal. 27(15/17):2765-2774. NAL Call #: S590.C63.

Nitrate remains a contaminant of concern for users of well water. Well-water evaluation, either to assess nitrate contamination or to evaluate sites prior to including them in a larger water quality study, often involves costly laboratory analysis. A cost effective alternative to laboratory analysis are dip-style test strips. However, the accuracy of these types of products must be reliable, as failure to identify the contaminant may, for example, persuade a homeowner to neglect to have a potential problem further investigated. The testing of nitrate using such strips typically involves dipping the strip into the water sample and reading the color development after a specific period of time. The color development is then compared to a color scale which corresponds to concentration provided with the test. The results of these types of analysis are especially open to interpretation by the evaluator of the results. An experiment was conducted to evaluate test strips in which individuals or "readers" tested water samples collected in the field and nitrate standards prepared in the laboratory with nitrate test strips. The results obtained by the "readers" were compared to analysis of nitrate by high performance liquid chromatography and colorimetric analysis using a colorimetric ion analyzer.

Border Health Office. Undated. An Assessment of Public Water Supply Systems in Dona Ana and Luna Counties. New Mexico Border Health Office.

Estimates national indicator and pathogen occurrence. 135 wells were sampled. Indicators monitored were male specific coliphage, total coliform, fecal coliform, and fecal enterococci. Enterovirus was monitored by cell culture.

Clark, R.M., J.A. Goodrich, B.W. Lykins, Jr., and J.R. Neal. (1998) Evaluating the Effects of Upstream Dischargers on Downstream Water Supplies: A Source Water Protection Model. Aqua 47(5):215.

Davis, J.V. and Witt, III, E.C. (2000) Microbiological and Chemical Quality of Ground Water Used as a Source of Public Supply in Southern Missouri- Phase I, May 1997-March 1998. Water -Resources Investigations Report 00-4038, 77 pp., USGS, US DOI, Rolla, Missouri.

Estimates national indicator and pathogen occurrence. Samples were taken at 109 wells. Indicators monitored were somatic coliphage, male specific coliphage, fecal streptococci, fecal coliform, and *E. coli*. Enterovirus was monitored by cell culture and PCR.

Delabre, K., E. Ferveur, S. Billard, C. Robert, and M.R. de Roubin. (2001) Use of Molecular Methods for the Detection of Waterborne Microorganisms. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

The development of increasingly efficient analytical methods is indispensable to ensure a high standard of water quality and to react rapidly against crisis situations. Molecular detection methods have many advantages in comparison with the traditional detection methods. They are more sensitive and specific and they allow a decreased time of analysis. The goal of this paper is to show the benefit of the use of molecular methods for the detection of waterborne bacteria based on the experience in our laboratory. This benefit will be demonstrated based on two examples: (i) the use of PCR for the detection of pathogenic bacteria in karstic areas and (ii) the use of DVC-FISH for the detection of *E. coli* in river and drinking water samples.

Di Giovanni, G.D., J.W. Czajka, A.M. Stoltzfus, Z. Bukhari, M.W. LeChevallier, and R. Aboytes. (2001) Evaluation of the BAX System PCR Assay for Screening *Cryptosporidium parvum*. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

The current US EPA Methods 1622 and 1623 use the immunofluorescence assay (IFA) for the detection of *Cryptosporidium* in water samples. The IFA is prone to false positives due to algal cells and does not specifically distinguish the human pathogenic *Cryptosporidium parvum* from other *Cryptosporidium* species, which are of little or no threat to human health. Molecular alternatives to current pathogen detection methods offer increased sensitivity, specificity and rapid analysis. The BAX System PCR Assay for Screening *Cryptosporidium parvum* (DuPont Qualicon) combines primers for the *C. parvum* heat shock protein 70 (hsp7O) gene and other PCR reagents in tablet form, prepackaged in a PCR tube. The primers detected the *C. parvum* bovine and human genotypes, the most common causes of human cryptosporidiosis. The primers also detected the *C. parvum* murine genotype, and *C. wrairi*, a genetically closely related species. They did not detect *C. serpentis, C. muris* or *C. baileyi*. Water sample preparation for the BAX System for *Cryptosporidium parvum* assay was almost identical to US EPA Method 1622/1623, providing water testing laboratories a simple progression to the BAX System. Samples were analyzed using the Automated BAX System instrument with closed- tube, fluorescent melting curve analysis detection and identification of specific PCR product, with complete analysis in approximately 4 hours. Sensitivity assays were carried out with mock IN4S samples spiked directly with single oocysts isolated by micromanipulation. Subsequent spiked mock IMS sample processing included buffer washes, centrifugation concentration and freeze thaw lysis of oocysts with positive results obtained for 6 out of 10 assays. Similarly, mock IMS samples spiked directly with 5 oocysts isolated by micromanipulation gave positive results for 10 out of 10 assays. Trials with 100 L drinking water IN4S concentrates spiked with 10 oocysts and processed as described above gave positive results for 5 out of 5 assays. Quantitative detection trials using the BAX PCR *Cryptosporidium parvum* reagents and the ABe 7700 instrument demonstrated that the amplification of 10, 5, and I oocysts could clearly be distinguished. Quantitation software for the Automated BAX System instrument is currently being developed. This assay provides the water industry with a molecular *C. parvum*-specific alternative to the IFA assay for screening water samples.

Doherty, K. (1998) Status of the New England Ground Water Viral Study. *Proceedings, American Water Works Association Annual Meeting, Dallas, Texas, June 23, 1998.* American Water Works Association, Denver.

Estimates national indicator and pathogen occurrence. Studied 124 wells in six states. The indicators monitored were male specific coliphage, somatic coliphage, total coliform, *Aeromonas hydrophila*, *C. perfringens*, *E. coli*, and enterococci. Enterovirus was monitored using cell culture and PCR.

Dorner, S.M., P.M. Huck, and R.M. Slawson. (2001) The Use of Modelling to Develop a Pathogen Monitoring Program in a Mixed-Use Watershed. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

This paper describes the initial phases of an ongoing research program aimed at determining sources of pathogenic microorganisms within a watershed. Preliminary modelling will be used to develop an effective and efficient monitoring program to maximize information regarding the origins of selected pathogens by determining appropriate sampling locations, frequency of sampling, and other environmental data necessary for predicting pathogen survival and transport. The objectives of this research are to develop a model that will be used to evaluate management alternatives aimed at reducing pathogen loads to a watercourse used as a drinking water source for half a million people in Southwestern Ontario, Canada.

Eastern Virginia Medical School, Center for Pediatric Research. (2001) Detection of Caliciviruses in Drinking Water. AWWARF Project No. 345.

Develops a molecular-based assay to detect a broad range of calicivirus strains. Applies the assay to environmental samples and determines the occurrence of caliciviruses in source, finished, and ground waters.

Edzwald, J.K. and M.B. Kelley. (1998) Control of Cryptosporidium: from Reservoirs to Clarifiers to Filters. Reservoir Management and Water Supply: An Integrated System. Water Science and Technology 37(2):1.

Femmer, S. (2000) Microbiological and Chemical Quality of Ground Water Used as a Source of Public Supply in Southern Missouri - Phase II, April-July, 1998. Water-Resources Investigations Report 00-4260, US DOI, USGS, Rolla Missouri.

Estimates national indicator and pathogen occurrence. Sampled 109 pre-1970 wells. Indicators monitored were somatic coliphage, male specific coliphage, fecal streptococci, fecal coliform, and *E. coli*. Enterovirus was monitored through cell culture.

Focazio, M.J., Z. Szabo, T.F. Kraemer, A.H. Mullin, T.H. Barringer, and V.T. dePaul. (2000) Occurrence of Selected Radionuclides in Ground Water Used for Drinking Water in the United States: A Targeted Reconnaissance Survey, 1998. U.S. Geological Survey Water-Resources Investigation Report 00-4273.

This USGS reconnaissance survey focused intentionally on areas with known or suspected elevated concentrations of radium in ground water to determine if Ra-224 was also present in the areas where other isotopes of radium had previously been detected and to determine the co-occurrence characteristics of the three radium isotopes (Ra-224, Ra-226, and Ra-228) in those areas. Ninety-nine raw water samples (before water treatment) were collected once over a 6-month period in 1998 and 1999 from wells (94 of which are used for public drinking water) in 27 States and 8 physiographic provinces.

Francy, D., Helsel, D., and Nally, R. (2000) Occurrence and Distribution of Microbiological Indicators in Groundwater And Stream Water. Water Environment Research, 72(2).

Estimates national indicator occurrence. Sampled 130 wells including 24 USGS monitoring wells. Indicators monitored were total coliform, fecal coliform, and *C. perfringens*.

Fraser, R.H., P.K. Barten, and D.A.K. Pinney. (1998) Predicting Stream Pathogen Loading from Livestock Using a Geographical Information System-Based Delivery Model. Journal of Environmental Quality 27(4):935.

Fu-Chih Hsu, Choi-Iok Wong, James Larkin, Earl Hansen, Mitt Denney, and Chris Hoesli. (2001) Detection and Species Identification of *Cryptosporidium* in River Water Samples Using EPA Method 1623 and PCR-RFLP. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

> The recoveries of *Cryptosporidium* using Method 1623 in 50 L of reagent water and PE samples were 60% and 62%, respectively with 11 % RSD. In 10 L of matrix spikes, the mean recovery was 42% with 13% RSD. The results indicate that Filta-Max filter gave sufficient recovery from different matrics with a low RSD. To facilitate the sampling process in the field, a simple, convenient, and fast sampling apparatus was constructed and tested. Of 19 surface water samples, 7 were positive for *Cryptosporidium* by Method 1623 with a range of 1 to 10 oocysts per 10 L. Among these 7 positive samples, 5 were also positive for *Cryptosporidium* by PCR. *C. parvum* bovine strain were identified by the RFLP in 4 of these surface water samples. One sample contained both *C. parvum* bovine strain and *C. muris*. All 12 samples negative by Method 1623 were negative by PCR. The results demonstrated a high degree of agreement (95%) between the two methods. The results prove it is feasible to use single filter (Filta- Max) to detect the presence of *Cryptosporidium*, confirm that presence, quantify the numbers of oocysts, and identify the species of *Cryptosporidium* present in surface water samples.

Fujioka, R.S. and Yoneyama, B.S. 2001. Assessing the Vulnerability of Groundwater Sources to Fecal Contamination. Journal AWWA.

> Estimates national indicator and pathogen occcurrence. Sampled 32 wells for viruses and 39 for bacteria. Indicators monitored were male specific coliphage, somatic coliphage, total coliform, *E. coli*, fecal streptococci, and *C. perfringens*. Pathogenic viruses monitored were *Legionella sp.,* and *Legionella pneumophila*

Gailey, R.M. and S.M. Gorelick. (2001) Design of Optimal, Reliable Plume Capture Schemes: Hagedorn, Charles. Bacterial Source Tracking. Articles retrieved from the World Wide Web on January 21, 2002: http://www.bsi.vt.edu/biol_4684/BST/BST/html. http://216.55.25.242/sw_0105_detecting.html http://216.55.25.242/sw_0106.detecting.html.

> The articles within this website provide discussions of bacterial source tracking (BST), a new methodology that is being used to determine the sources of fecal bacteria in environmental samples (e.g., from human, livestock, or wildlife origins). BST is also called fecal source tracking and/or fecal typing. It is expected that these methods will assist in the development and implementation of TMDLs.

Goyal, S.M., Amundson, D., Robinson, R.A. and Gerba, C.P. (1989) Viruses and drug resistant bacteria in ground water of southeastern Minnesota. *Jour. of the Minnesota Academy of Science*, 55:58-62.

Estimates national indicator and pathogen occurrence. Sampled 24 wells and 2 springs in SE Minnesota. Somatic coliphage was the indicator monitored. Enterovirus was the pathogenic virus monitored by cell culture.

Guillot, Emmanuelle and Melanie Fontaine. (2001) Development of a Quantitative Real-time PCR Assay for *Cryptosporidium parvum* in Water Samples. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

The public health problem posed by *Cryptosporidium parvum* has urged the water supply industry to develop very accurate analytical tools to assess the presence of this parasite in water. The classical method based on indirect immunofluorescence assay (IFA) routinely used for the detection of *Cryptosporidium* oocysts in water is time-consuming and non-specific for *C. parvum*, the species which affects humans. In order to circumvent these limitations, a quantitative test based on real-time quantitative PCR using the TaqMan fluorogenic detection system (TaqMan PCR) was developed. TaqMan PCR identified a 138 base pair section of a *Cryptosporidium parvum* genomic sequence by using a specific fluorogenic probe and two primers. This system used the high performance of DNA polymerase for nucleic amplification and a 5'nuclease assay with an internal fluorogenic DNA probe for real-time quantitation. Fluorescence intensity was directly proportional to the copy number of the *C. parvum* target DNA sequence and was detected with an automated fluorometer. Quantitation was accomplished by comparing the fluorescence signals obtained from samples with unknown numbers of *C. parvum* oocysts with fluorescence signals from *C. parvum* oocysts standard dilutions. This real time quantitative PCR assay allows reliable quantitation of *C. parvum* oocysts over a 6-log dynamic range within three hours. This molecular test will be very useful for the water industry: it can be used for drinking water quality control as well as for the evaluation of treatment efficiency and the identification of risk resources.

Hogben, Peter and Brian Drage. (2001) Use of a Chemical Sensor and an On-line Flow Cell for Monitoring Water Quality. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

Water and water tainted with 2-chlorophenyl at varying concentrations was used to assess the use of a chemical sensor array to monitor for changes in the head space generated from an on-line flow cell. Results demonstrated that the head space generated could be successfully used to detect the presence of organic pollutants in water using an array of chemical sensors. Current work is focusing on the sensitivity of the sampling system., investigating the effects of different real water types on the detection of pollutants, and developing data analysis protocols to identify real-time changes in water quality.

International Life Sciences Institute. (1999) Early Warning Monitoring to Detect Hazardous Events in Water Supplies. An ILSI Risk Science Institute Workshop Report. Retrieved from the World Wide Web: http://www.ilsi.org/file/EWM.pdf

The ILSI Risk Science Institute convened a two-day specialty workshop in May 1999 that focused on three specific areas: threats to drinking water supplies from low-probability /high public health impact events; early warning monitoring approaches; and interpretation, risk management, and public communications issues. This report is concerned primarily with the detection of hazardous events in source water.

International Life Sciences Institute. (2000) Revised Framework for Microbial Risk. Results available on the World Wide Web: http://www.ilsi.org

Reports on trials of a conceptual model for conducting waterborne microbial risk assessments that was developed in 1995. Includes exercises of the model for Cryptosporidium and rotavirus.

Karim, M., LeChevallier, M., Abbaszadegan, M., and J. Rosen. (2002) Field testing of USEPA method 1601 for coliphage. AWWARF

Estimates national indicator and pathogen occurrence. Sampled 20 wells. Indicators monitored were male specific coliphage, somatic coliphage, total coliform, *E. coli*, enterococci, and *Clostridium perfringens*. Pathogenic viruses sampled by cell culture and RT-PCR were enteric virus, enterovirus, Norwalk virus, rotavirus, presumptive HAV, and presumptive adenovirus.

Lee, JiYoung and Rolf A. Deininger. (2001) Rapid Detection of *Pseudomonas aeruginosa* and *Legionella pneumophila* in Water. Presented at AWWA Water Quality Technology Conference, Nashville, Tennesse, November 11-15, 2001.

The purpose of this study was to evaluate a rapid method (<l hour) for the detection of *Pseudomonas aeruginosa* and *Legionella pneumophila* in water. For this, immunomagnetic separation (IMS) and a detection method, ATP bioluminescence, have been investigated. The magnetic beads were coated with the antibodies, which are specific for either *P. aeruginosa* or *L. pneumophila*. The artificially inoculated water was used. The immunomagnetically separated bacteria were measured by both ATP bioluminescence method and plate count method. Various experimental conditions were tested to find the shortest reaction time while obtaining high recovery. Different concentrations of antibody-magnetic bead complex that capture target bacteria were also tested. The results showed that a reaction time between 10 and 30 min is long enough to allow the reaction between bacteria and antibody-magnetic bead complex. The optimal concentration of antibody-bead complex was 5 µl per ml of sample. The comparison of the level of the target pathogens captured by IMS with the initial level of the bacteria

followed a very similar pattern. The results appear promising for a rapid on-site assay of pathogens within an hour without enrichment process.

Lieberman, Richard J. (Continuing) Viral and Microbial Methods for Groundwater. AWWARF and U.S. EPA. Duration: December 16, 1991 to September 30, 1995.

Will evaluate new screening technologies with conventional tissue culture methods to monitor for the presence of enteric viruses in groundwater. Will also include surrogate indicators such as total coliforms, fecal coliforms, coliphage, *E. coli, Clostridium* spp., etc. Will determine which microbial indicators are best for monitoring enteric viruses.

Lieberman, R.J., Shadix, L.C., Newport, B.S., Frebis, C.P., Moyer, M.W.N., Safferman, R.S., Stetler, R.E., Lye, D., Fout, G.S., and Dahling, D. (2001) "Microbial monitoring of vulnerable public ground water supplies." AWWA Research Foundation and AWWA, p. 154.

Estimates national indicator and pathogen occurrence. Phase I sampled 94 wells in 22 states plus Puerto Rico and the U.S. Virgin Islands. Indicators monitored were somatic coliphage, total coliform, *E. coli*, enterococci, and *C. perfringens*. Phase II sampled 30 wells, 23 of which were from Phase I, from 17 states plus Puerto Rico and the U.S. Virgin Islands. Indicators monitored were somatic coliphage, male specific coliphage, *Bacteroides* bacteriophage, total coliform, *C. perfringens*, and *E. coli*. Pathogenic viruses monitored were *Legionella pneumophila*, enterovirus, heptatis A virus, Norwalk virus, reovirus, and rotavirus.

Lindsey, B.D., Raspberry, J.S. and Zimmerman, T.M.. (2002) Microbiological quality of water from noncommunity supply wells in carbonate and crystalline aquifers of Pennsylvania. U.S. Geological Survey Water-Resources Investigations Report 01-4268, p. 30.

Estimates national indicator and pathogen occurrence. Sampled a total of 60 wells from karst, fractured bedrock, sandstone, and sand settings. Indicators monitored were male specific coliphage, somatic coliphage, total coliform, *E. coli*, enterococci, *C. perfringens*, and *H. pylori*. Enterovirus was monitored by cell culture.

Louisiana Department of Environmental Quality. (1997) Early Warning Organic Compound Detection System. Retrieved October 21, 2001 from the World Wide Web: http://www.deq.state.la.us/surveillance/ewocds/

The Early Warning Organic Compound Detection System (EWOCDS) is a volatile organic compound (VOC) sampling program using a network of gas chromatographs and data transmitting devices to provide warning of possible contamination of drinking water supplies on the Mississippi River. It is designed to provide data on river water quality, and could serve as a deterrent to the surreptitious discharging or spilling of organic wastes into the Mississippi River.

McDevitt, James J. and Kellogg J. Schwab. (2001) Development of a Rapid Molecular Detection Method for *Toxoplasma gondii* oocysts. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

> Infections caused by *Toxoplasma gondii* are widely prevalent in animals and humans throughout the world. In the United States, an estimated 23% of adolescents and adults have laboratory evidence of infection with *T. gondii. T. gondii* has been identified as a major opportunistic pathogen in immunocompromised individuals, in whom it can cause life threatening disease. Water contaminated with feces from domestic cats or other felids may be an important source of human exposure to *T. gondii* oocysts. Because of the lack of information regarding the prevalence of *T. gondii* in surface waters, there is a clear need for a rapid, sensitive method to detect *T. gondii* from water. Currently available animal models and cell culture methods are time consuming, expensive, and labor-intensive, requiring days to weeks for results to be obtained. Detection of *T. gondii* nucleic acid by the polymerase chain reaction (PCR) has become the preferred method. We have developed a PCR amplification and detection method for *T. gondii* oocyst nucleic acid that incorporates the use of hot start amplification to reduce non specific primer annealing, Uracil-N-glycosylase to prevent false- positive results due to carryover contamination, an internal standard control to identify false-negative results due to inadequate removal of sample inhibition, and PCR product oligoprobe confirmation using a nonradioactive DNA hybridization immunoassay. This method can provide positive, confirmed results in less than one day. Using cloned *T. gondii* DNA, detection sensitivity is less than 200 femtograms. Less than 100 oocysts can be detected following recovery of oocyst DNA. Development of a *T. gondii* oocyst PCR detection method will provide a useful technique to estimate the levels of *T. gondii* oocysts present in surface waters.

Ohio River Valley Water Sanitation Commission. (No Date) Organics Detection System. Retrieved November 15, 2001 from the World Wide Web: http://www.orsanco.org/

> As part of the Spill Notification and Tracking Program, ORSANCO maintains the Organics Detection System to assure that unreported releases or spills of organic compounds do not compromise drinking water intakes. Fifteen gas chromatographs on the Ohio, Allegheny, Monongahela and Kanawha Rivers are operated daily. If an organic compound is detected, ORSANCO is notified and the presence of the compound in the river is validated. Once validated, the information is distributed to downstream water utilities, as well as state and federal agencies. Summary data is published in the ORSANCO's Quality Monitor.

Patterson, Glenn G. and Michael J. Focazio. (2001) Contaminants and Drinking-Water Sources in 2001: Recent Findings of the U.S. Geological Survey. Open-File Report 00-510.

The work includes monitoring to determine the spatial and temporal distribution of contaminants; research to determine sources, transport, transformations, and fate of contaminants, and assessments of vulnerability. Much of the work is conducted in cooperation with EPA and other Federal, State, Tribal, and local governments, to help provide a scientific basis for resource management and regulation. Examples of recent results are presented for two broad categories of drinking-water projects: occurrence studies, and source-water assessments.

Pillai, S. (1997) Virus sampling and microbial analysis at the U.S.-Mexico border for the U.S. Environmental Protection Agency. Unpublished report for The Cadmus Group, Inc

Estimates national indicator and pathogen occurrences. Sampled 17 wells in Texas and New Mexico. Indicators monitored were male specific coliphage and somatic coliphage. Enterovirus was monitored through cell culture.

Pitt, R., M. Lalor, J. Harper, C. Nix, and D. Barbé. (2000) Potential New Tools for the Use of Tracers to Indicate Sources of Contaminants to Storm Drainage Systems. *In* National Conference on Tools for Urban Water Resource Management and Protection. Proceedings. Chicago, IL. February 7-10, 2000. EPA/625/R-00/001.

A description of previously developed methods used to identify sources of contaminants in storm drainage systems, plus a review of emerging techniques that may also be useful. The original methods, along with selected new procedures, were tested using almost 700 stormwater samples collected from telecommunication manholes from throughout the U.S.

Seiler, R.L., S.D. Zaugg, J.M. Thomas, D.L. Howcroft. (1999) Caffeine and Pharmaceuticals as Indicators of Waste Water Contamination in Wells. USGS, Carson City, Nevada. Ground Water 37(3):405.

Slifko, T.R., D. Friedman, J.B. Rose, and W. Jakubowski. (1997) An In Vitro Method for Detecting Infectious Cryptosporidium Oocysts with Cell Culture. Applied and Environmental Microbiology 63(9):3669.

Tan, Seet and Leslie Gammie. (2001) Using an On-line UV Monitor as a Pollution Alarm. Presented at AWWA Water Quality Technology Conference, Nashville, Tennessee, November 11-15, 2001.

Concern over possible contaminants coming from storm sewer outfalls have resulted in a search for a on-line pollution alarm monitor which can do rapid analysis in time to take action on the treatment of the water. The Kontron On-line UV monitor with an analysis time of a minute appeared to be capable of acting as a pollution monitor. It measures the standard deviation (SD) of the baseline of 1,000 UV scans of the source water from 240 ηm to 290 ηm. It will compare the standard deviations of any new scan with that of the last scan and generate a value known as the Last Scan Difference (LSD). When the LSD is significantly different from its baseline normal standard deviations, a pollution alarm is triggered. The results from two periods of system operation indicated that the baseline standard deviation was identical regardless of season and differences in the source water. A few "alarm" events occurred, but attempts to identify pollutants during an alarm event by testing for target compounds were unsuccessful.

University of North Carolina at Chapel Hill. (1997) Enteric Virus Detection in Water by Nucleic Acid Methods. AWWARF Project No. 612.

Develops a rapid, sensitive and specific method for the detection of viruses in drinking water by amplification of viral nucleic acids followed by detection using nonradioactive gene proves.

USEPA. (2002) Ground Water Rule Occurrence and Monitoring Document. Prepared by The Cadmus Group; Arlington, VA. Contract 68-C-02-026. June 2002.

One of seven regulatory support documents issued in conjunction with promulgation of the GWR. It provides background for all GWR regulatory support and guidance documents, but is used primarily to support analyses of the national risks and the national costs and benefits presented in the Economic Analysis (EA). This document provides background information regarding the contaminants in drinking water sources regulated under the GWR.

USEPA. (1998a) Wisconsin Migrant Worker Camp Drinking Water Quality Study. Unpublished report prepared for US EPA Region V, Safe Drinking Water Branch, July, 1998, p.10.

Estimates national indicator occurrence. Sampled 21 wells. Indicators monitored were male specific coliphage, total coliform, *E. coli*, and *K. pneumoniae*.

USEPA. (1998b) Ground Water Rule Vulnerability Assessment Study, April 3, 1998. Unpublished report prepared by International Consultants, Inc. for the Office of Ground Water and Drinking Water, p. 29.

Estimates national indicator and pathogen occurrence. Sampled 30 wells in eight states. Indicators monitored were male specific coliphage, somatic coliphage, total coliform, and enterococci. Pathogenic viruses monitored by cell and PCR were enterovirus, HAV, rotavirus, and Norwalk virus.

Vaughn, J.M. (1996) Sample Analyses. Attachment, unpublished letter on the analysis of alluvial wells in Missouri by Jerry Lane, Missouri Department of Natural Resources, Rolla, MO, November 7, 1996.

Estimates national indicator and pathogen occurrence. Sampled 64 wells. Indicators monitored were somatic coliphage, male specific coliphage, *Bacteroides* bacteriophage, total coliform, fecal coliform, and fecal streptococci. Enterovirus was monitored by cell culture.

Wilshire, H.G. and I. Friedman. (1999) Contaminant Migration at two Low-Level Radioactive Waste Sites in Arid Western United States: A Review. Environmental Geology 37(1/2):111.

Wisconsin State Laboratory of Hygiene. (1997) Detection of Cryptosporidium and Giardia by Flow Cytometry. Published as "Using Flow Cytometry to Detect Protozoa" in Journal AWWA 89(9):104-111.

Evaluates the use of flow cytometry to improve detection of *Giardia* and Cryptosporidium using the immunofluorescence assay.

Wisconsin State Laboratory of Hygiene and Indiana University Kokomo. (2000) Evaluation of Antibodies to *Cryptosporidium* and *Giardia* Using Flow Cytometry. AWWARF Project No. 358.

Provides a protocol for evaluating various antibodies that can be used for the detection of Cryptosporidium and *Giardia* in water samples. Includes methods of correlating specific properties of antibodies and methods of correlating antibody activities between different types of assays.

Ongoing Research

DOE, Sandia National Laboratories. (2000) News Release: Sandia's Portable Chemical Vapor Detection System Being Prepared for "Big" Test. Retrieved January 31, 2002 from the World Wide Web: http://www.mdl.sandia.gov/sensors/sensor_techinfo.html

Sandia is developing a lightweight, portable chemical vapor detection system that shows promise for rapid detection of chemicals in the environment. An array of seven surface acoustic wave (SAW) sensors with different chemically sensitive thin film coatings can detect trace levels of airborne contaminants. The low-cost light weight system can identify 18 different VOCs, as well as nuclear and biological chemicals in the field in minutes. Preparation for a field test simulating a chemical release is underway.

Environmental Engineering & Technology, Inc. Occurrence of, and Problems Associated With, Trace Contaminants in Water Treatment Chemicals. AWWARF Project No. 2600. To be completed in 2002.

> This study will determine the extent and nature of the occurrence of trace impurities in water treatment chemicals. It will also identify the types of problems that utilities experience and the difficulties they encounter in meeting finished water standards and in disposing residuals because of the presence of these impurities.

Environmental Engineering & Technology, Inc. Treatment of MF and UF Residuals for Removal of Cryptosporidium, Viruses, and Other Contaminants Prior to Recycling. AWWARF Project No. 2724. Research partners: Utilities in CA, TX, AZ and FL. To be completed in 2004.

> The research team will characterize the extent and nature of water quality deterioration as it relates to microbial fouling and regrowth in reclaimed distribution systems. It will also determine the operational procedures to best meet the needs of utilities for operation of reclaimed water storage/distribution systems and will provide guidelines for the operation and maintenance of these systems.

Georgia Institute of Technology. Field Transport of Cryptosporidium Surrogate in Small Catchments Used for Grazing Lands. AWWARF Project No. 2566. To be completed in 2002.

> This project will study the natural movement of colloidal-sized particles such as Cryptosporidium at an undisturbed field site used for cattle production. Will also improve approaches to modeling oocyst transport in unsaturated soils using existing water flow and transport models.

Grayman, Walter and University of Michigan. Design of Early Warning and Predictive Source Water Monitoring Systems. AWWARF Project No. 2527. To be completed in 2001.

> This project involves developing early warning and source water monitoring systems for real-time contaminant monitoring. These systems would allow operators to predict water quality events that may tax subsequent treatment processes.

Ho, C.K., M. Kelley, M.T. Itamura, and R.C. Hughes. (2001) Review of Chemical Sensors for In-Situ Monitoring of Volatile Contaminants. SAND2001-0643. March. Retrieved January 31, 2002 from the World Wide Web: http://www.sandia.gov/sensor/SAND2001-0643.pdf

> This report presents a review of sensors and technologies that are capable of detecting and monitoring volatile organic compounds. Four general categories of sensor technologies were reviewed: (1) chromatography and spectrometry; (2) electrochemical sensors; (3) mass sensors; and (4) optical sensors. Based on the review criteria set forth

in this report, the most viable sensors for in-situ chemical sensing appear to be electrochemical sensors (specifically conductometric sensors), fiber-optic sensors, and surface-acoustic-wave sensors. However, very few chemical sensors have been successfully demonstrated in realtime, continuous, in-situ applictions.

Kiwa, N.V. Innovative Systems for Early Warning Water Monitoring. AWWARF Project No. 2779. To be completed in 2003.

The project team will develop and evaluate new and innovative systems to rapidly detect chemicals (individual or classes), radioactivity, pathogens, or biotoxins in water in order to help make these systems more viable for use by the drinking water community.

Metropolitan Water District of Southern California (Los Angeles) and McNamee, Porter & Seeley, Inc. Early Warning Techniques and Communication Plans for Surface Water Taste-and-Odor Events. AWWARF Project No. 2614. To be completed in 2002.

This project involves developing predictive tools or methods for taste-and-odor (T&O) events in lake, reservoir, and river sources. Will review and adapt existing, successful water quality tests, sensory methods, and remote sensing technologies used in water supply and other industries for the prediction of T&O events. Will also conduct a survey of existing successful customer communication strategies to proactively communicate T&O events to the public.

Provincial Laboratory of Public Health for Northern Alberta and University of Alberta. Waterborne Gastrointestinal Disease Outbreak Detection. AWWARF Project No. 447. To be completed in 2001.

The project team will produce a guidance manual for drinking water and public health professionals that will assist them in establishing tracking systems for early detection of gastrointestinal disease outbreaks. Continuous input of health data from health care institutions for an information base will be used.

University of California at Riverside, U.S. Salinity Laboratory, State of Florida Dept. of Health and Rehabilitative Services, University of Arizona, and University of South Florida. Measurement of Virus and Indicator Survival and Transport in the Subsurface. AWWARF Project No. 262. Published in 2000.

This project develops a scientific basis for “natural disinfection” criteria in the Ground Water Disinfection Rule (GWDR). Assesses the potential for developing indicators of viral contamination of groundwater and will obtain data that can be used to test the virus transport model used in the development of the existing numerical values for the proposed "natural disinfection" criteria.

University of Delaware and University of California at Riverside. Inactivation Rates of Viruses and Bacteria in Saturated and Unsaturated Subsurface Media AWWARF Project No. 353. To be completed in 2002.

> This project will determine the inactivation rates of pathogenic human enteric viruses, bacteria, and bacteriophages in saturated and unsaturated soils and aquifer materials under a variety of environmental conditions (e.g., temperature, pH, moisture content, etc.). Will also determine the critical soil factors that influence the survival of pathogenic microorganisms in the subsurface media. Will discuss the significance of the results to "natural disinfection" in relation to the Ground Water Disinfection Rule and to utility groundwater management efforts.

University of Massachusetts. Development of F-Specific Coliphage Typing for Source Water Protection/Watershed Management. AWWARF Project No. 2822. To be completed in 2003.

> This project will investigate whether specific subtyping of F-specific coliphages can be used to discriminate among specific sources of contamination. It will enumerate and isolate F-specific coliphages from various sources including sewage and animal feces. If subtyping proves successful in differentiating between sources of contamination, field validation of subtyping methods by enumerating and analyzing coliphages present in surface waters subjected to a variety of known land uses and fecal contamination sources will be performed.

University of Massachusetts at Amherst. Development of Event-Based Pathogen Monitoring Strategies for Watersheds. Research Partner: U.S. EPA. AWWARF Project No. 2671. To be completed in 2004.

> This project will develop and validate a strategy for selection of sampling location, frequencies and methods to accurately depict pathogen occurrence and variability in relation to various sources within watersheds during and after weather, hydrologic or land-use events.

University of North Carolina at Chapel Hill. Development of a Molecular Method to Detect Infective Viruses. AWWARF Project No. 2591. To be completed in 2003.

> This project involves developing a molecular method to detect infectious viruses in water. The project team will verify the method by comparison to available cell culture methods.

U.S. Department of Agriculture. Advancing *Cryptosporidium parvum* Detection Methodologies. AWWARF Project No. 2502. Research partner: U.S. EPA. To be completed in 2002.

This effort will further advance the application of nucleic acid amplification, cell culture, enzyme-linked immunosorbent, and fluorescent in situ hybridization techniques for the detection of *Cryptosporidium parvum*.

U.S. Geological Survey. Development and Implementation of Random-Walk Particle Tracking Analysis of Water Supply Intakes on Rivers and Lakes: A Case Study of St. Clair-Detroit River Waterway. AWWARF Project No. 2743. Research partner: City of Detroit Water & Sewerage Dept. To be completed in 2004.

Will develop methodology and enhance existing software to quantitatively assess the vulnerability of water supply intakes on rivers and lakes to discharges from tributaries, combined sewer overflows, and spills.

WERF. (No Date) Detection of Pathogens and Indicators: Real-Time PCR. WERF Project No. 01-HHE-2a. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

This effort will examine the feasibility of more rapid and specific detection methods (quantitative polymerase chain reaction) for pathogen and indicator monitoring. This could lead to near real-time analysis of human health risk.

WERF. (No Date) Detection of Pathogens and Indicators: Microarray Technology. WERF Project No. 01-HHE-2b. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

This project compares a more rapid and specific detection method (microarray technology) for pathogen and indicator monitoring with existing U.S. EPA methods. This could lead to near real-time analysis of human health risk.

WERF. (No Date) Overcoming Molecular Sample Processing Limitations: Fiber-Optic Biosensors. WERF Project No. 00-HHE-2C. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

To take advantage of new molecular techniques for the detection of pathogens and indicator organisms, this research will test the sensitivity and specificity of a fiber-optic biosensor for real-time detection of bacterial pathogens. Will provide alternatives to conventional measurements of water quality.

WERF. (No Date) On-line Trace Contaminant Monitoring at Municipal Water and Wastewater Treatment Plants. WERF Project No. 01-WSM-2c. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search

> This research tests the feasibility of using an existing online technology to detect and measure trace metals in water and wastewater. Could improve monitoring techniques and responsiveness to potential upsets.

WERF. (No Date) Developing Novel, Low-Cost Sensors for Environmental Monitoring. WERF Project No. 00-CTS-12-ET. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

WERF. (No Date) Overcoming Molecular Sample Processing Limitations: New Platform Technologies. WERF Project No. 00-HHE-2A. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

> To take advantage of new molecular techniques for the detection of pathogens and indicator organisms, this research will evaluate novel technologies for the automated, rapid detection of bacteria, viruses, and protozoa. Will provide alternatives to conventional measurements of water quality.

WERF. (No Date) Overcoming Molecular Sample Processing Limitations: Quantitative PCR. WERF Project No. 00-HHE-2B. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

> To take advantage of new molecular techniques for the detection of pathogens and indicator organisms, this research will develop simple standardized protocols for rapid quantitative PCR detection of total and viable *Cryptosporidium* and infectious enteroviruses in wastewater. Will provide alternatives to conventional measurements of water quality.

WERF. (No Date) HANAA for Waterborne Pathogen Detection. WERF Project No. 99-HHE-4-ET. Project completed; final report currently being reviewed for publication later in 2001. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search

> Results indicate that the handheld advanced nucleic acid analyzer (HANAA) — a novel, miniaturized, real-time, thermal cycler instrument — can successfully amplify DNA from *Cryptosporidium* and *E. coli*. The probes detected *Cryptosporidium* and *E. coli* 0157:H7 DNA in PCR reactions performed on the HANAA. Although it is currently an emerging technology, future commercial versions of the HANAA may be useful instruments for laboratories performing PCR assays for waterborne pathogen detection.

WERF. (No Date) Stormwater Environmental Indicators Pilot Demonstration Project. WERF Project No. 96-IRM-3. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search

This report demonstrates the Center for Watershed Protection's Stormwater Indicator Methodology for use in the semi-arid west.

WERF. (No Date) Workshop on Molecular Approaches for Alternatives in Indicator Monitoring and Pathogen Assessment. WERF Project No. 00-HHE-3. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

This project will explore diverse information on molecular characterization, identification, and monitoring that can be assembled for a new framework for microbiological water and wastewater analysis. Will identify currently available methods and protocols, as well as knowledge gaps.

WERF. (No Date) Field Calibration and Verification of a Pathogen Transport Model. WERF Project No. 00-WSM-3. Retrieved October 29, 2001 from the World Wide Web: http://www.werf.org/research/search/

This project will evaluate the magnitude and character of transported loads of *Cryptosporidium parvum* oocysts from controlled plots to verify and calibrate a transport model.

Wisconsin State Laboratory of Hygiene. Assessment of Source Waters and Drinking Waters for Estrogenic Endocrine Disruptors. AWWARF Project No. 2642. To be completed in 2003.

This project will modify, validate, and utilize in vitro screening tests for the presence of estrogenic compounds in water samples. It will also perform in vivo tests in combination with in vitro tests to determine the significance of the presence of estrogenic compounds in source waters, finished drinking waters, and effluent streams.

Wisconsin State Laboratory of Hygiene, University of Arizona, and Clancy Environmental Consultants. Development of a Method for Recovery of Microsporidia from Source and Finished Waters. AWWARF Project No. 2590. To be completed in 2003.

The researchers will develop a method to recover Microsporidia that are pathogenic to humans from source and finished waters.

Response Systems

Recent Research

AEC Notify News. (2001) New Environmental Construction Technology Debuts at Army Corps of Engineers Small Business Exposition.

Discusses introduction of Uniloc sheet pilings that use a new patented interlocking system to provide an in-the-ground barrier against the migration of chemical spills and toxic materials. Uniloc products provide toxi waste retention,l underground hydrocarbon tank leak containment, farmland pesticide and fertilizer run-off control, segregation, and disposal of hydrocarbons from highway runoff.

Burrows, W. Dickinson and Sara E. Renner. (1999) Biological Warfare Agents as Threats to Potable Water. Environmental Health Perspectives 107(12):975.

Committee to Review the New York City Watershed Management Strategy, National Research Council. (2000) Watershed Management for Potable Water Supply: Assessing the New York City Strategy. National Academy Press, Washington, DC.

In 1997, New York City adopted a mammoth watershed agreement to protect its drinking water and avoid filtration of its large upstate surface water supply. The NRC's evaluation of this agreement found that it is a good template for proactive watershed management that, if properly implemented, will maintain high water quality. However, the Committee cautions that the agreement does not guarantee that filtration can be permanently avoided because of changing regulations, uncertainties regarding pollution sources, advances in treatment technologies, and natural variations in watershed conditions.

Environmental News Network. (1999) Microbes Tested in Groundwater Cleanup. September 30, 1999.

Provides a news story of the ability of microbes to clean up pesticide-contaminated groundwater, making it safe for drinking water or domestic use. Working with native Australian soil microbes that have been found to break down atrazine, the team has devised an underground "curtain" to strip the pesticide out of flowing groundwater. The method is being tested on a 1,300 foot plume of atrazine that lies underneath the town.

U.S. EPA. Oil Pollution Prevention Regulation Overview. Retrieved from the World Wide Web: http://www.epa.gov/oilspill/opprover.htm.

Spill Prevention Plans. Retrieved from the World Wide Web: http://www.epa.gov/oilspill/spccplan.htm

What SPCC Plans Must Include. Retrieved from the World Wide Web: http://www.epa.gov/oilspill/spccmust.htm

Li, J. (2001) GIS Planning Model for Urban Oil Spill Management. Water Science and Technology 43(5): 239.

Perth, Western Australia. The Contaminated Groundwater Plume Is the Result of a Chemical Spill. Retrieved from the World Wide Web, January 7, 2002.

EPA Region III. (1999) Chemical Emergency Preparedness and Prevention Conference (CEPP). Proceedings and Notes at www.epa.cepp.com (Url not working as of January 18, 2002).

Galt, J.A. (1999) The Integration of Trajectory models and Analysis into Spill Response Information Systems. Spill Science & Technology Bulletin 4(2): 123.

> The spill response community is engaged in a technological rush towards computer-based, information-synthesis systems. These are modeled after many successful 'incident command' or 'command and control' systems that use micro or mini computer technology. Virtually all of these systems offer spill trajectory modeling components. What is typically lacking in this modeling output is any reliable way to estimate the uncertainty. A discussion of options suggests that the adoption of a minimum standard analysis procedure would significantly improve the ability of integrated response systems to use the predictions of oil distributions.

Gorelick, S.M., A.R. Freeze, D. Donohue, and J.F. Keely. (1993) Groundwater Contamination: Optimal Capture and Containment. Lewis Publishers, Boca Raton, Florida.

> Delineates a total of six options for containing or remediating groundwater contamination sites.

Minnesota Pollution Control Agency. (2001). What Is Natural Attenuation? Retrieved from the World Wide Web: http://www.mpca.gov

Plavecsky, Jim. (1996) Absorbing Reading on Spill Cleanup. Environmental Protection 7(9):28.

> Key terms: chemical spill prevention, absorbent choice and disposal, toxicity characteristics, leaching procedure, and method overview.

Rattle, J. (No Date) Groundwater Contamination from Industrial Landuse. Retrieved January 12, 2002 from the World Wide Web: http://www.uoguelph.ca/~jrattle.lit.html.

> Reviews a study of chemicals leaking from the Chemspec Industries chemical plant in Southern Ontario into the groundwater beneath. The surveys will include the Brandywine River, in order to confirm the suspected detrimental effects of

contamination on the river. One remediation strategy may be to develop an upper aquifer groundwater containment system.

Singh, S.M., R.H. Green, and R.C. Bailey. (1986) Bivalve Molluscs as Response Systems for Modelling Spatial and Temporal Environmental Patterns. Science of the Total Environment 46(11):147.

Tierney, K.J., M.K. Lindell, and R.W. Perry. (2001) Facing the Unexpected: Disaster Preparedness and Response in the United States. Joseph Henry Press, New York.

Presents information derived from disasters around the world over the past 25 years. The authors explore how these findings can improve disaster programs, identify remaining research needs, and discuss disaster with the broader context of sustainable development. The authors review the influences that shape the US governmental system for disaster planning and response, the effectiveness of local emergency agencies, and the level of professionalism in the field. They also compare technological versus natural disasters and examine the impact of technology on disaster programs.

Upper Mississippi River Basin Association. (2000). Minutes of the Upper Mississippi River Hazardous Spills Coordination Group Meeting. Retrieved January 7, 2002 from the World Wide Web: http://www.umrba.org/web%20docts/meetings%

Provides summaries of discussions held by members of the UMR Hazardous Spills Coordination Group at their regional meetings and summaries of on-going research by presenters and the Committee.

Ongoing research

Colorado State University. Surviving Disasters: Building on Experience. AWWARF Project No. 2696. To be completed in 2002.

This effort will identify research needs and will attempt to synthesize existing information related to the impact of natural disasters on water treatment facilities.

Duke Engineering and Services, Inc. Avoiding Negative Outcomes from Emergency Events. AWWARF Project No. 2636. To be completed in 2003.

This research will capture existing knowledge and approaches used by utilities and other industries to minimize the possibility of an emergency event, to proactively mitigate consequences of possible emergency events, and to prepare for response and recovery from emergency events. It will focus on addressing the needs of the water utility customer before and after emergency events.

Duke Engineering and Services, Inc. Workshop for Identifying and Prioritizing Emerging Safety Issues in the Water Industry. AWWARF Project No. 2684. To be completed in 2002.

The purpose of this research is to determine the scope and magnitude of safety issues in the drinking water industry and identify potential research responses for these issues, as well as potential research partners.

Mohanty, Kishore K. (1994) Impermeable Barriers for Underground Contaminant Containment. Environmental Institute of Houston Bulletin No. 1, Summer.

Slurry trenching has been used to provide a barrier, but the technique has several limitations. Researchers plan to evaluate the effectiveness of polymeric and silica gel materials for the formation of barriers to the transport of NAPLs and aqueous organic and ionic contaminants. Development of these barrier technologies will allow containment of expanding plumes of underground contaminants and reduce future remediation costs.