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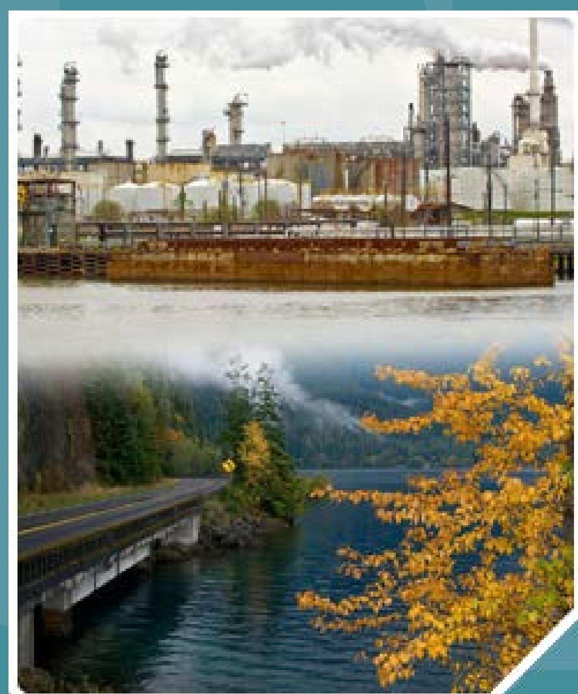
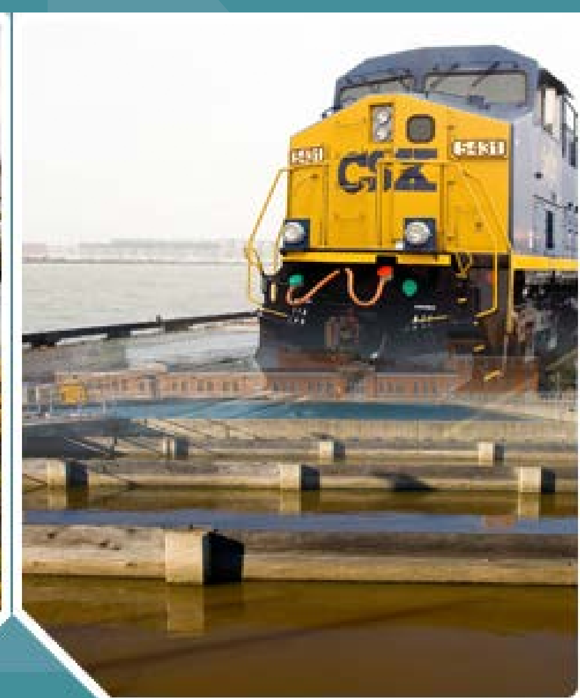
Drinking Water Treatment Source Water Early Warning System State of the Science Review Report





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Drinking Water Treatment Source Water Early Warning System State of the Science Review

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Disclaimer

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The contractor role did not include establishing Agency policy.

Table of Contents

Appendix A Table of Contents

List of Tables

List of Figures

List of Appendix Tables

List of Appendix Figures

Abbreviations

AAS	atomic absorption spectroscopy
ANN	artificial neural network
BBN	Bayesian Belief Network
BTEX	benzene, toluene, ethylbenzene and xylene
CBOD	carbonaceous biochemical oxygen demand
CDOM	chromophoric dissolved organic matter
COD	chemical oxygen demand
COG	Council of Governments
CSO	combined sewer overflow
DAEWS	Danube Accident Emergency Warning System
DBP	disinfection byproduct
DDM	Data-driven model
DHS	U.S. Department of Homeland Security
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DRBC	Delaware River Basin Commission
DWMAPS	Drinking Water Mapping Application to Protect Source Waters
EEM	excitation-emission matrix
EWOCDS	early warning organic contaminant detection system
EWS	early warning system
FDOM	fluorescent dissolved organic matter
GA	genetic algorithm
GC	gas chromatograph(y)
GC-FID	gas chromatography flame ionization detector
GC-MS	gas chromatography – mass spectrometry
GIS	geographic information system
GNOME	General NOAA Oil Modeling Environment
HAA	Haloacetic Acid
HAB	harmful algal bloom
HEC-RAS	Hydrologic Engineering Center's River Analysis System
IC	ion chromatography
ICP-MS	inductively coupled plasma – mass spectrometry
ICPDR	International Commission for the Protection of the Danube River
ICP-MS	inductively coupled plasma – mass spectrometry
ICPRB	Interstate Commission of the Potomac River Basin
ICWater	Incident Command Tool for Drinking Water Protection
ILSI	International Life Sciences Institute
LC	liquid chromatography
LC-MS	liquid chromatography – mass spectrometry
LEPC	Local Emergency Planning Committee
LPCF	linear prediction coefficient filter
MCHM	4-methylcyclohexanemethanol

MVE	minimum volume ellipsoid
MWRDGC	Metropolitan Water Reclamation District of Greater Chicago
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NRC	National Response Center
ODS	Organics Detection System
ORP	oxidation-reduction potential
ORSANCO	Ohio River Valley Water Sanitation Commission
PA DEP	Pennsylvania Department of Environmental Protection
PAH	polycyclic aromatic hydrocarbon
PARAFAC	Parallel Factor Analysis
PCB	polychlorinated biphenyl
PCR	polymerase chain reaction
PLSR	partial least squares regression
POC	particulate organic carbon
PWD	Philadelphia Water Department
RAIN	River Alert Information Network
RNA	ribonucleic acid
ROC	receiver operating characteristic
RSI	Risk Science Institute
RTU	remote terminal unit
RWQMN	Remote Water Quality Monitoring Network
SCADA	supervisory control and data acquisition
SMS	Short Message Service
SRBC	Susquehanna River Basin Commission
SRS	surveillance and response system
TEVA	Threat Ensemble Vulnerability Assessment
THM	trihalomethane
TOC	total organic carbon
TSS	total suspended solids
UASI	Urban Area Security Initiative
UMR	Upper Mississippi River
UMRBA	Upper Mississippi River Basin Association
U.S.	United States
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UV	ultraviolet
UV-vis	ultraviolet-visible
VOC	volatile organic compound
WSSC	Washington Suburban Sanitary Commission
WVAW	West Virginia American Water

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Executive Summary

In the United States, customers expect and receive an adequate supply of high quality water when they turn on their taps. However, under some relatively rare circumstances, contaminants might find their way into the drinking water resulting in unacceptable water quality. One important element in the control of water quality is the detection of contaminants in the water prior to its delivery to the customers. Early warning systems (EWSs) have been developed to coordinate and systematize these activities. This report is a state-of -the-science review of source water EWSs. The report evaluated several key studies conducted in the early 2000s to establish the current state-of-the-science and practice for source water EWSs. The report also identifies key research areas that need to be addressed to improve EWS.

The first modern EWS was formed after a significant leak of carbon tetrachloride from a chemical tank into the Kanawha River moved downstream into the Ohio River in 1977. Other EWSs were established around the world in response to different contamination incidents. Following the terrorist attacks in New York City and Washington, DC on September 11, 2001, emphasis in the area of EWSs shifted to concerns over contamination of drinking water distribution systems and resulted in robust research and development, and implementation of warning systems in many distribution systems. Almost 40 years after the carbon tetrachloride spill to the Kanawha River initiated the interest in EWSs, a chemical spill to the Elk River in West Virginia just upstream of the Kanawha River in 2014 has reinvigorated the interest in surface water contamination EWSs.

Contamination incidents have been caused by a wide range of sources including industrial and transportation related spills, non-point sources and urban runoff, intentional contamination and natural processes. EWSs encompass much more than just sensors or monitors; rather they include mechanisms for detecting, characterizing, communicating and responding to contamination incidents in order to initiate effective response actions, and reduce and mitigate the impacts. The general state-of-the-science of sensor and monitoring technologies, event detection methodologies, contamination incident modeling tools, and data integration and communication are presented. EWSs have been implemented around the world as a mechanism for detecting the presence of contaminants or water quality anomalies in surface waters. The characteristics and practices of 8 domestic EWSs and 6 international EWSs are summarized in this report. Detailed descriptions are provided for nine of the most robust systems worldwide.

Although significant research has been conducted on the separate components of an EWS (e.g., monitoring technologies, event detection methodologies, modeling tools), additional research needs to be conducted to evaluate EWSs as a whole to better understand their performance, detection capabilities and limitations. In addition, future research needs were identified as part of this study for each of the components and key needs are summarized below.

- To improve the effectiveness of a source water EWS, more information is needed on the contaminants that might be a possible threat. This could include developing tools that enable better access to contaminant information in the watershed.
- Monitoring technologies research should focus on determining the best parameters to monitor, understating the field performance of various monitoring technologies, evaluating monitoring technologies through bench, pilot and field scale testing, and developing more reliable, practical, and accurate monitoring technologies.

- Placement research could help identify where monitors should be located with the source water to be the most effective for the purposes of the early warning system.
- Fate and transport research should focus on models that could be used to support source water early warning systems. This could include developing approaches to link real-time data with surface water modeling and simulation tools, incorporating the whole watershed into the models, and developing linkages between the fate and transport models and GIS databases.
- Detection methodology research needs are associated with the application of EDS to source water applications. These needs could include better understand current false positive detection rates and what causes them, developing libraries of events/alarms associated with common contaminants, and developing additional EDS techniques that could explore the use of artificial neural networks.
- EWS requires data management and visualization tools to support analytics and communication. Some research needs identified in the study include the development of: better data transmission tools to support monitor at remote sensing locations, enhanced data analysis and visualization tools to support real-time response actions, and a reliable method for validating data from online instruments in real-time.

1.0 Introduction

Customers expect that when they turn on the tap, they will receive an adequate supply of high quality water. In most situations in the United States, that expectation is met. However, under some relatively rare circumstances, contaminants might find their way into the drinking water, resulting in unacceptable water quality.

Generally, the pathways that water follows from source to tap are complex and lengthy. Surface water or groundwater moves through natural and/or constructed conveyance to a collection point, where it is delivered to a water treatment plant in which various forms of treatment are applied. The treated water then enters a distribution system where it is delivered to customers via piping, pumps, valves and tanks. Within the natural and constructed delivery system, there are many opportunities for contaminants to enter the water and degrade the quality of the water.

Two important elements in the control of water quality delivered to customers is the detection of contaminants in the water, and the treatment or other intervention prior to its delivery to the customers. Detection can be through monitoring or observation. Intervention can be through increased treatment, through management of the water to keep the contaminated water from being delivered to the customer, or through issuing “do not drink,” “do not use,” or “boil water” warnings until the contaminants have been eliminated or reduced to an acceptable level. Early warning systems (EWSs) have been developed to coordinate and systematize these activities.

This report is a state-of-the-science review of source water EWSs. The report updates several key studies conducted in the early 2000s to establish the current state of the science. Monitoring and contamination warning systems within distribution systems and wastewater systems have been widely studied and are addressed in this report when they can contribute to the understanding of source water EWSs.

1.1 Definition and Goals of Early Warning Systems (EWSs)

EWSs have been developed to detect a wide range of natural or human induced incidents including earthquakes, landslides, tsunami, volcanic eruptions, floods, epidemics, wildfires, harmful algal blooms (HABs) and contamination incidents. The commonality across the spectrum of incident types is that early warning systems generate information that empowers decision makers to take action in time to avoid or mitigate human health risks, economic losses, or other bad outcomes of disasters and hazardous conditions. If well integrated with risk assessment studies and with communication and action plans, early warning systems can lead to substantive benefits (UNEP, 2012). When applied to contamination incidents, EWSs are intended to identify low-probability/high-impact contamination incidents in sufficient time to be able to safeguard the public (Storey et al., 2011).

1.2 A Brief History of Source Water EWSs

An incident in the Ohio River Basin in 1977 led to the development of one of the first modern EWSs to combat source water contamination. A significant leak of carbon tetrachloride, from a chemical storage facility to the Kanawha River, moved downstream into the Ohio River over a period of several months. At the time, routine monitoring was not conducted on the Ohio River that would have detected this chemical. Rather, its presence was discovered when Ohio River water in Cincinnati, Ohio, was tested for carbon tetrachloride as part of a United States Environmental Protection Agency (U.S. EPA) research project. The incident led to the establishment of the Ohio River Valley Water Sanitation Commission (ORSANCO) Organics Detection System (ODS) (Hadeed, 1978).

As was the case with the EWS established on the Ohio River, other EWSs were established around the world in response to contamination incidents. For example, in 1986, a fire at the Sandoz Company in Switzerland resulted in a large chemical spill in the Rhine River and the subsequent implementation of monitors and an EWS on the Rhine River. Other major EWSs were established in Japan, Canada, the Netherlands and other places around the world. A state of the art of source water early warning systems at the end of the twentieth century, as documented in Brosnan (1999), Grayman et al. (2001) and Gullick et al. (2003), is presented in Chapter 2.

Following the terrorist attacks on New York City and Washington, DC on September 11, 2001, emphasis in the area of EWSs shifted to potential intentional contamination of water distribution systems. Research, development and implementation of warning systems in distribution systems was robust. The name of such warning systems was changed to contamination warning systems in recognition that warnings based on detection of contaminants already in the distribution system would likely not be early enough to prevent all exposure. The U.S. EPA has recently referred to such systems as water quality surveillance and response systems (SRS) to reflect the broader mission of such systems in detecting and responding to water quality threats (U.S. EPA, 2015).

Almost 40 years after the carbon tetrachloride spill to the Kanawha River initiated the interest in EWSs, a chemical spill to the Elk River in West Virginia, just upstream of the Kanawha River, has reinvigorated the interest in surface water EWSs (Bahadur and Samuels, 2015).

1.3 Types of Incidents and Conditions that Source Water EWSs Address

Contamination that can affect drinking water sources could originate from many types of incidents. These incidents could be one-time spills of short duration, an ongoing discharge, or a recurrent contaminant incident based on seasonal or meteorological/hydrologic conditions. The following is a list of some of the potential types of contamination incidents:

- Industrial spills: facility leaks, tank rupture/leakage
- Transportation related spills: ships, trucks, barges, loading facilities
- Urban runoff: combined sewer overflows, surface runoff
- Non-point sources: agricultural runoff, urban runoff, erosion
- Intentional contamination: terrorists, vandals, illegal disposal of hazardous substances
- Natural occurrences: algae blooms, organic material (particularly disinfection byproduct precursor materials)
- Treatment facilities: insufficient treatment, malfunctioning due to power losses, flooded facilities

Figure 1 depicts the different types of potential contamination sources as well as the monitoring locations that could be associated with an EWS.

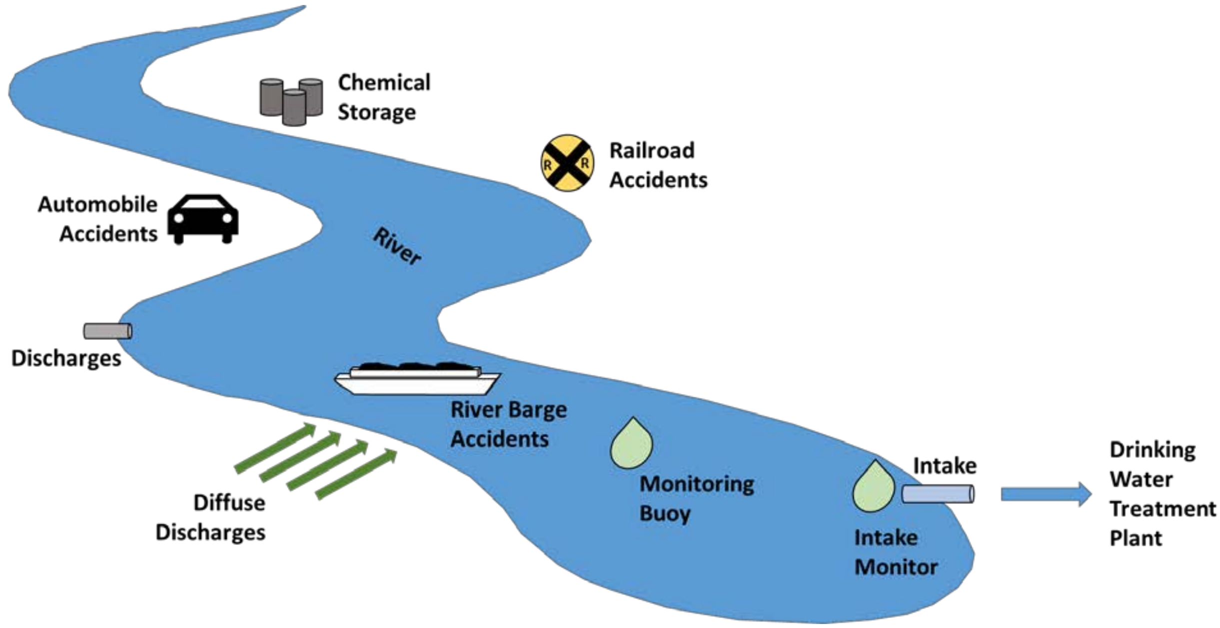

Figure 1. Potential sources of contamination that could affect a drinking water intake.

1.4 Components of an EWS

Grayman et al. (2001) and Gullick et al. (2003) described the following components of an EWS:

- *Detection* is a mechanism for recognizing the likely presence of a contaminant in the source water. Detection might include continuous monitoring, sporadic or periodic monitoring, public reporting of suspected contamination and self-reporting of contamination incidents. A relatively new development involves automated event detection software that uses time series information from monitors and other supporting information to identify anomalous behavior that might indicate the occurrence of a contamination incident and notify EWS operators.

- *Characterization* is the process of determining what happened during a contaminant incident. Gullick et al. (2003) outlined a six-step process for characterizing contamination incidents and synthesizing data and other information into knowledge better suited for use by staff in response to an incident. The six steps proposed were (i) determine the specific contaminant(s) involved, (ii) identify the contaminant source, (iii) determine the temporal and spatial variation in contaminant concentration(s) in the source water, (iv) assess the dynamic behavior of the contaminant in water (mixing and physicochemical transformation), (v) predict the movement of the contaminant in water and (vi) determine the effects on the waterway itself.

- *Response coordination* is an institutional framework generally composed of a centralized unit that coordinates the efforts associated with managing the contamination incident.

- *Communication*, in this context, is a means to link and transfer information related to the contamination incident.

- *Mitigation* is a means of responding to the presence of contamination in the source water in order to reduce or eliminate its impact on water users.

Figure 2 shows a schematic illustrating data flow and utilization in an integrated EWS. (SCADA stands for supervisory control and data acquisition.)

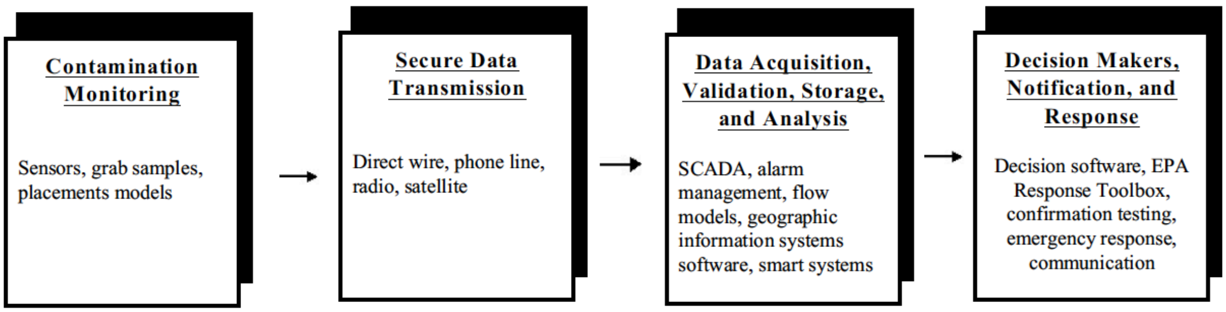

Figure 2. Design features of an integrated early warning system (EWS) (U.S. EPA, 2005).

2.0 Review of Early Warning System (EWS) Applications

Early warning systems (EWSs) have been implemented around the world as a mechanism for detecting the presence of contaminants or water quality anomalies in surface waters. In this chapter, the need for such systems is documented along with a review of the characteristics of many of the EWSs that have been implemented. One specific type of contaminant incident, HABs, has emerged in recent years as a significant challenge to the drinking water community. Early warning activities focused on detecting HABs differ significantly from activities focused on most other water quality contaminants and are addressed in detail in this chapter.

2.1 Establishing the Need for EWS

In order to identify the extent of source water monitoring and EWSs, Grayman et al. (2001) conducted a survey of drinking water utilities. A large majority of the utilities were located in the United States with a smaller number located in Canada and the United Kingdom. Primary emphasis was placed on surface water sources that were considered to be most vulnerable to short-term contaminant incidents. Additional details on the survey results can be found in Gullick (2003). Of the 210 utilities that were contacted, 153 responded to the survey. Treatment plant sizes varied from 0.15 to 1500 million gallons per day (0.0066 to 65.72 cubic meters per second). A majority of the 153 utilities that responded to the survey had experienced a significant contamination incident within the previous five years. Many utilities reported inadequate warning and response time during these incidents. Utility staff were most concerned about transportation accidents. The most common contaminants were:

- Oil and petroleum products
- Algae and bacteria
- Particulates
- Ammonia and volatile organics
- Pesticides/herbicides/insecticides from industrial spills
- Agricultural runoff
- Untreated sewage
- Seasonal urban runoff

Less than half of the utilities surveyed had an EWS although 90% of them viewed these systems as important in the future. Only 25% engaged in source water monitoring beyond regulatory requirements.

Brosnan (1999) reported on the results of a two-day workshop convened by the International Life Sciences Institute’s (ILSI) Risk Science Institute (RSI) with 60 scientists from four countries. The workshop was to determine the state of the science for EWS to identify strengths and weaknesses of existing technologies and strategies; to raise awareness of transient hazardous incidents; and to promote research into prevention, detection, mitigation and treatment. The workshop determined that the most commonly perceived threats included spills of oil and industrial products from pipelines, tanks and transportation corridors; insecticides and herbicides from agricultural runoff; and pathogens from untreated sewage runoff or spills. The most common EWSs in operation were for chemical and radioactive materials, while monitoring systems for microbial incidents were less common. Intentional threats, such as water system sabotage or bio-warfare, were not common. Most U.S. utilities monitored some source water characteristics, but these included a limited number of parameters and were generally conducted no more than once a week.

2.2 EWS Applications

Source water EWSs in the United States date back to the mid-1970s with the development of the ORSANCO ODS (Hadeed, 1978). It has served as a model in the development of subsequent regional systems. Over the past 40 years, the use of EWSs for drinking water sources has expanded with improvements to previously existing systems, implementation of new systems and ongoing development of future systems. Since the early development of EWSs, their use has been enhanced with advancements in monitoring technologies, improved modeling and communications and the inclusion of additional measured constituents; for example, biomonitoring and advanced remote sensing enable detection and early warning of toxicity and HABs. The current application of EWSs encompasses multiple large surface water sources with a significant national coverage area including the Delaware River Basin, Lake Erie, the Lake Huron to Lake Erie corridor, the Lower Mississippi River Basin, the Ohio River Basin, the Susquehanna River Basin, the Upper Mississippi River Basin and others. Internationally, the use of EWSs has also expanded including development in Africa, China and Europe. Table 1 presents an alphabetical list of source water EWSs identified in the literature search for this report. The table provides a quick summary of the system along with references to find out more information. The literature search focused on regional systems and not systems in place at a single drinking water treatment plant or intake. Detailed descriptions of a few of EWSs are provided in Appendix A of this report.

Table 1. Early Warning System (EWS) Summaries

Location	Summary	References*
Canada *North Saskatchewan River*	EPCOR Utilities in Canada uses two stations at intakes to monitor source water for chemical dosing decision support. EPCOR is a private water, wastewater and power supplier whose sole shareholder is the City of Edmonton, Canada.	Gullick et al. (2003)
China *Yellow River*	Responsibility for water quality monitoring and protection in China falls under the purview of the Ministry of Water Resources, the Ministry of Environmental Protection and the National Environmental Monitoring Center. The seven major rivers in China are the Yangtze River, Yellow River, Pearl River, Songhua River, Huaihe River, Haihe River and Liaohe River. China's water quality monitoring network of source water includes more than 100 stations. A five-year initiative promoting collaboration between the European Union and China led to the development of an EWS on a section of the Yellow River. Additional EWSs have been tested and/or implemented at other locations.	Burchard-Levine et al. (2012); CNEMC (2009); European Commission (2012); Ministry of Environmental Protection (2015); Zhang et al. (2012)
Danube and Tisza River Basin *Danube and Tisza Rivers*	Managed by the International Commission for the Protection of the Danube River (ICPDR), the Danube Accident Emergency Warning System (DAEWS) was implemented in 1997 in Austria, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Romania, Slovakia and Slovenia; in 1999, the system was extended to Ukraine and Moldova and in 2005, expansion included Bosnia-Herzegovina and Serbia (ICPDR, 2016). An EWS is also being explored for the Tisza River Basin, the largest tributary to the Danube. The existing DAEWS is primarily a communications network and consists of a partnership of stakeholders, a periodic water quality monitoring network, an international communication and alert system and a web and database portal. The proposed Tisza River EWS includes continuous water quality monitoring with real-time data transmission (VRIC & EI, 2014). More information on DAEWS is provided in Appendix A.1.	ICPDR (2011, 2014, 2015a, 2015b, 2016); IWAC (2001); VRIC and EI (2014)
Delaware Valley *Delaware and Schuylkill Rivers*	The Delaware River Basin is comprised of the Schuylkill River and Delaware River watersheds. Home to approximately 8 million residents, the region spans 13,500 square miles in parts of Delaware, New Jersey, New York and Pennsylvania (DRBC 2013). Led by the Philadelphia Water Department (PWD), the EWS was implemented in 2004. The EWS consists of 88 monitoring stations, and web- and phone-based incident reporting. It includes 25 water treatment plants and 24 industrial sites through a partnership between 300 participants from 50 organizations.	Anderson (2015); DRBC (2013); Duzinski (2008); Gullick et al. (2004)

Location	Summary	References*
	The system includes measurement of dissolved oxygen (DO), turbidity, temperature and conductivity. The Delaware Valley EWS is described in greater detail in section 2.4 and in Appendix A.2.	
Great Lakes *Lake Erie*	The Great Lakes HABs program is a collaborative effort between scientists at the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and the Cooperative Institute for Limnology and Ecosystems Research. Project goals are to provide a 5-day prediction of the severity and movement of HABs on Lake Erie. Satellite data, in conjunction with remote sensing buoys and a comprehensive physical monitoring program, is used to forecast HABs. Four remote sensing buoys collect data every 15 minutes; physical collection of samples is done weekly at eight locations. A forecast bulletin is issued up to every two days during the bloom season and an online HAB tracker is updated daily with a 5-day forecast. Real-time field measurements, laboratory data, satellite images and bulletins are publically available online. More information on this system is provided in Appendix A.3.	Stumpf et al. (2012); NOAA GLERL (2015a, b, c) NOAA GLERL (2016)
Lake Huron to Lake Corridor *St. Clair and Detroit Rivers and St. Clair Lake*	Starting in 2006, the Huron-to-Erie Real-time Drinking Water Protection Network was developed through a partnership between multiple agencies and participants including the U.S. EPA and the Michigan Department of Environmental Quality. The coverage area includes nine monitoring sites located at drinking water treatment plants. Water quality data are logged every 15–30 minutes; monitoring equipment measures pH, temperature, DO, conductivity, turbidity, oxidation reduction potential, chlorophyll, organic carbon, gasoline, diesel fuel, waste oils and other industrial chemicals. The system includes a database, web portal, and a communication and data sharing network. More information on the Huron-to-Erie Real-time Drinking Water Protection Network is provided in Appendix A.4.	Howard (2007); Lichota and DeMaria (2009); NexSens Technology (2016); Wrubel (2014)

Location	Summary	References*
Lower Mississippi River Basin *Mississippi River*	The early warning organic compound detection system (EWOCDS) was implemented in 1986 for the southern-most portion of the Lower Mississippi River, covering Louisiana from Baton Rouge to Plaquemines Parish (Wold, 2015). Water quality data are collected from seven monitoring stations. The EWOCDS monitors water draining from more than 40% of the continental United States; that water serves as drinking water source for 30% of Louisiana's population. Each location includes a gas chromatograph, with samples collected twice per day at most sites; two stations have continuous sampling. Monitoring stations measure 28 chemical contaminants including halogenated organic compounds, chlorinated hydrocarbons and trihalomethanes. Associated costs are covered by the Louisiana Department of Environmental Quality. In 2014, the EWOCDS benefitted from a settlement between Exxon Mobil and Louisiana, from which $250,000 was slated for additions and upgrades to the EWS. More information on EWOCDS is provided in Appendix A.5.	Louisiana DEQ (2016, 2014, 2012, 2009); Wold (2015); Waldon et al. (1998)
Nile River Basin *Nile River*	The Nile River Basin EWS was developed in 2008 with funding through North Atlantic Treaty Organization's Science for Peace Program with coordination from Egypt's Ministry of Water Resources and Irrigation, National Water Research Center. The EWS consists of a monitoring network and an internal database portal. The monitoring network consists of eight sites along the Nile River in Egypt. Real-time water quality monitoring equipment measures pH, DO, temperature, conductivity, ammonia and nitrate at 15 minute intervals. Data are accessible through an internal web portal. More information on the Nile River Basin EWS is provided in Appendix A.6.	Khan and Khan (2008); Khan et al. (2011)

Location	Summary	References*
Ohio River Basin *Ohio River*	Ohio River Valley Sanitation Commission's (ORSANCO's) organic detection system (ODS) was developed in 1977. It currently includes 16 stations at water utilities and industries along the Ohio River from the confluence of the Allegheny and Monongahela Rivers in Pennsylvania to the Mississippi River in Illinois. The ODS monitors water draining from greater than 150,000 square miles (388,498 square kilometers) and that serves as drinking water source for more than 22,000,000 people. Each station is equipped with a purge and trap gas chromatography system and tests for the presence of 30 purgeable organic compounds above trigger thresholds on at least a daily basis. The system also includes reporting of spill incidents from industries, river users and the National Response Center. ORSANCO coordinates emergency communications among water utilities and industry users along the river through an electronic bulletin, Short Message Service (SMS) messaging, email and a website for online data. The agency also manages the travel time and water quality modeling during a spill incident. The ORSANCO ODS is described in greater detail in section 2.4 and in Appendix A.7.	ORSANCO (2016a, 2016b); Schulte (2014)
Rhine River Basin *Rhine River*	The International Commission for the Protection of the Rhine operates nine international stations plus 20 national monitoring stations in Germany, Holland and Switzerland. The system uses biomonitors extensively.	Gullick et al. (2003)
River Alert Information Network (RAIN) *Allegheny, Monongahela, Beaver and Ohio Rivers*	The RAIN system is a voluntary cooperative effort of drinking water suppliers in western Pennsylvania and northern West Virginia. The effort includes water quality monitoring and data management. In addition, the effort includes data sharing among the participating utilities, state regulators and the general public. Active monitoring sites are on the Allegheny, Monongahela and Ohio Rivers. Monitored parameters include dissolved oxygen, conductivity, pH and temperature. In addition to maintaining a water quality monitoring and early warning capability, the RAIN system has a significant public education focus, intended to engage the public in understanding and protecting drinking water resources. The RAIN system maintains a publicly accessible website allowing visualization of current water quality data.	River Alert Information Network (2016)

Location	Summary	References*
Susquehanna River Basin *Susquehanna River*	Led by the Susquehanna River Basin Commission (SRBC), the Susquehanna River Basin EWS was implemented in 2003 and extended in 2006. The current coverage area in Pennsylvania and New York includes water suppliers serving approximately 700,000 people. Water quality data are collected with real-time data transmission from nine monitoring points for pH, temperature and turbidity, while TOC, conductivity and DO are additionally collected at some locations. Online tools enable water suppliers to access and analyze data with integrated mapping and a time-of-travel tool. The coupling of the water quality monitoring network with the SRBC's communication and data-sharing network enables access to the real-time monitoring data as well as important water-quality data collected by other agencies. More information on the Susquehanna River Basin EWS is provided in Appendix A.8.	Gullick et al. (2004); SourcewaterPA (2015); SRBC (2012, 2013a, 2013b, 2015, 2016)
United Kingdom *River Dee*	Three water companies, including Hyder Lab and Sciences, partnered with the government to install and operate three monitoring stations on the River Dee. Routine grab sampling and analysis are conducted at the monitoring locations as well as online monitoring. The River Dee EWS is described in greater detail in section 2.4.	Gullick et al. (2003)
Upper Mississippi River Basin *Mississippi River*	The Upper Mississippi River (UMR) Basin spans approximately 189,000 square miles in parts of Minnesota, Wisconsin, Iowa, Illinois and Missouri and is home to more than 30 million residents (Swanson, 2012). A pilot monitoring station was operated from 2003–2007. The UMR EWS was led by U.S. EPA and the Upper Mississippi River Basin Association. It consisted of six real-time monitoring stations with measurement of temperature, conductivity, DO, pH, turbidity, nitrate, total organic carbon (TOC), dissolved organic carbon (DOC) and toxicity (biomonitoring). More information on the UMR EWS is provided in Appendix A.9.	Allen et al. (2014); Gullick et al. (2003; 2004); Swanson (2012); UMRBA (2016, 2014, 2007)

*References are found at the end of the report.

2.3 EWS Case Studies

Interviews were conducted with the staff of five EWSs. The EWSs were chosen based on their different purposes and configurations and based on the availability and interest of the EWS staff in participating in the project. The intent of the interviews was to develop a deeper understanding of the purposes and challenges of EWSs and to identify practical constraints to their operation. Interviews were conducted using a script, though the interview facilitator asked unscripted follow-up questions when opportunities for additional data collection were presented. U.S. EPA initiated each interview by describing the purpose of the interview and U.S. EPA's efforts in source water event detection and early warning. Results from the five interviews are presented below.

2.3.1 Metropolitan Washington Council of Governments (COG)/Potomac

Since 2005, Potomac region water providers have worked with the Metropolitan Washington Council of Governments (COG) to develop and maintain a regional monitoring capability. The program was originally funded by an Urban Area Security Initiative (UASI) grant and the original purposes of the EWS were response to 9/11 and development of regional capacity for event detection and response. Early in the development of the EWS, basic finished water quality parameters were monitored by utilities drawing water from the Potomac River and by the utilities' wholesale customers. One participating utility used the Hach® GuardianBlue® (Hach, Loveland, CO) unit for managing data and event detection. Subsequently, source water monitoring was added at key locations along the Potomac River. At present, the system serves all utilities drawing water from the Potomac River as far as Brunswick, Maryland. Water quality monitoring currently in place at nine utilities includes Hach panels (measuring basic water quality parameters), fish monitors, radiation monitoring and online gas chromatography (GC) monitoring.

Online instruments are maintained on raw water for plants on the Potomac River and in finished water for some of the systems. Though the system is a regional system, operation of instruments and transfer of data is done by participating utilities and a significant challenge is instrument maintenance and communication of results among stakeholders. The Metropolitan Washington COG coordinates the monitoring efforts, purchases and facilitates maintenance of instruments and engages in planning and assessment. Instruments are operated by staff at utilities where instruments are deployed.

2.3.1.1 <u>EWS Specifics</u>

Monitoring is conducted at the City of Leesburg (Virginia), the Washington Suburban Sanitary Commission (WSSC), the Washington Aqueduct, Fairfax (Virginia), Brunswick (Maryland), Rockville (Maryland) and Frederick (Maryland). Each of those utilities also maintains additional online source water monitoring for process control (as opposed to event detection) and not connected with the regional monitoring program. Instruments in place online at the monitoring locations include Hach panels, fish monitors, one radiation monitor and, recently, two Inficon CMS5000 online GCs. With the exception of the online GCs, instruments (including fish monitors) collect water quality data at 1-minute intervals. Two portable GCs (Inficon Hapsites) are available for use in incident response or other purposes.

Data management differs by monitoring location. Communication with most of the Hach panels is via cellular modems and a commercial remote connection service. One of the utilities has included monitoring data in its supervisory control and data acquisition (SCADA) system to allow local staff to visualize trends and produce time series plots. At that utility, online monitors are interfaced with the SCADA system via Modbus® protocol, which enables communication between remote terminal units measuring the online water quality data and SCADA systems. Prior attempts to establish a regional online communication path/network have been subject to frequent telecommunication failures and improving communication remains a challenge for the EWS.

Improved coordination of monitoring and data sharing are stated goals for the EWS. Generally, monitoring locations/equipment are stand-alone and working independently. The Interstate Commission on the Potomac River Basin (ICPRB) manages data flow and has developed a formalized program for spill notifications and data sharing. A single industrial partner provides data directly to ICPRB in the incident of a spill.

2.3.1.2 *Prior Experience and Future Development*

To date, online monitors have detected relatively harmless plant incidents such as chemical feed backflows, though challenge testing indicates that both water quality monitors and the fish monitors respond to changes in water quality quickly. Utilities have separate protocols for responding to incidents detected by online monitors. At one of the utilities, incidents are recorded in an electronic logbook and responses are directed from the utility control center.

The greatest current challenges for the EWS are communication and data management and analysis. At present, online monitoring data are not managed centrally and are managed differently by the program’s partners. Communication includes management of data within utilities, between utilities, with the EWS and with external organizations such as ICPRB and incident response centers. For some of the participating utilities, communication needs include getting data into a SCADA system for improved access and use by plant staff. Protocols for sharing data among utilities have been written, but have not been assessed fully or implemented.

Near-future development is planned for both the physical system and the administrative structure. Utilities are interested in expanding the role of monitoring from detection of contaminants and incidents to more general collection of water quality data for other purposes such as operations support. Specific interests include use of fluorescence/spectral instruments for algae detection, detection of hydrocarbons, and detailed monitoring of organic matter.

2.3.2 Ohio River Valley Sanitary Commission (ORSANCO)

ORSANCO is a regional organization that supports utilities in the Ohio River Valley. ORSANCO manages a regional organics detection system (ODS) as part of their core function. The ORSANCO’s ODS program entails continuous water quality monitoring and contaminant early warning at a regional scale. The impetus for the ORSANCO ODS was a series of high-impact contamination incidents on the Ohio River and its tributaries. One of the most important of those incidents was a 1977 release of carbon tetrachloride in the Kanawha River that impacted drinking water supplies on the Kanawha and Ohio Rivers including for Huntington, West Virginia, Portsmouth, Ohio, and Cincinnati, Ohio.

Monitoring equipment used in ORSANCO’s ODS is a series of gas chromatographs (GCs) owned by ORSANCO and operated by participating utilities. As currently configured, the ODS can be considered a screening program because of limitations in the number of monitoring locations and the range of parameters that can be monitored routinely. Quality assurance and quality control (QA/QC) procedures were established specifically for the ODS to ensure data quality without causing excessive demands for utility laboratory staff.

ORSANCO's primary stakeholders are participating utilities. ORSANCO and utilities maintain open communication and ORSANCO facilitates the transfer of data between utilities. ORSANCO's overall funding ($2.6-$3 million annually) is from the member states and U.S. EPA, while the ODS program is funded exclusively by the states. Stakeholders beyond participating utilities include states and two industrial dischargers (in Parkersburg, West Virginia and Saint Albans, West Virginia). ORSANCO serves many groups, including the U.S. Coast Guard (USCG) and other entities involved in spill response. Utilities provide significant in-kind support as staff time to conduct analyses and facilities to house equipment.

2.3.2.1 *EWS Specifics*

Organics monitoring is conducted at 16 locations, with 13 on the Ohio River main stem and the rest on the major tributaries (Kanawha River, Allegheny River and Monongahela River). Instruments are housed and operated at participating utilities and include gas chromatography – mass spectrometry (GC-MS) and GC with flame ionization detector (GC-FID) as well as online GC analyzers. In routine monitoring, samples are analyzed for 30 organic compounds four times per day and online GC analyzers operate at two-hour intervals. Utilities commit to report all detections greater than 2 ppb, but generally report detections greater than 1 ppb. Samples are collected in duplicate for confirmatory or more detailed analysis. During emergency response, utilities might be asked to analyze additional samples at intervals as short as one hour.

Data are reported to and maintained by ORSANCO. At least every week, the data are downloaded and reviewed by ORSANCO staff. The reviews are more frequent after/during spills and following spurious detections. After a spill, data are shared with all participating utilities and chromatographs are shared with downstream utilities. Chromatographs could also be shared with state regulatory agencies, though historically states have not requested them. ORSANCO does not plan to share data with the general public, though states or utilities could choose to share data. ORSANCO is currently developing a web-based tool for internal data maintenance and utilization.

In the event of a detection during routine sampling, ORSANCO performs additional QA/QC on the data. Once results are verified, ORSANCO requests the utility partner to collect an additional sample and downstream utilities, state regulatory agencies and the NRC are notified. After spills or other incidents, data might be used in concert with modeling to predict and track contaminant plumes. The Ohio River main stem and major tributary hydraulic/hydrologic information (predicted river depths and flows for the next five days) are provided to ORSANCO by the U.S. Army Corps of Engineers (USACE) on a daily basis (weekdays only except during flood conditions when data might also be provided on weekends). These data are generated by the USACE CASCADE model (currently being transitioned to the HEC-RAS model) and used by ORSANCO as input to predictive river water quality models when a spill occurs.

ORSANCO conducts numerous activities related to the ODS and EWS such as bi-monthly nutrients and metals monitoring, fish and macroinvertebrate monitoring, and combined sewer overflow (CSO) long-term control plan tracking. Online monitoring for routine water quality parameters and for cyanotoxins are in development.

2.3.2.2 *Prior Experience and Future Development*

The ODS and ORSANCO are operational and an integral component of Ohio River Valley emergency response. The ODS has been used in the following incident responses over the past five years:

- A 10,000-gallon diesel spill in Cincinnati, Ohio, that was not detected by the ODS.
- The Freedom Industries 4-methylcyclohexanemethanol (MCHM) spill (Elk River), in which the ODS detected MCHM at the nearest downstream monitoring location (St. Albans, West Virginia).
- A methylene chloride release in Cincinnati, Ohio, that was detected by the ODS. In addition, the ODS was used to help identify the source.
- An ethanol spill from derailed train cars, in which the associated diesel fuel was detected by the ODS, but ethanol was not.

ORSANCO expects the ODS to continue operation for the foreseeable future. ORSANCO identified a number of improvements and enhancements it is considering. Algae monitoring for HAB early warning could be added and could include monitoring on reservoirs and the deployment of multi-parameter probes. ORSANCO is also interested in improved access to information on contaminants in the Ohio River Valley such as shipping cargo information, inventories of compounds carried on rail cars, and an inventory of contaminants stored in the Ohio River Valley watershed.

2.3.3 Delaware Valley EWS

The Delaware Valley EWS was established in the 2004 and 2005 timeframe using grants from the U.S. EPA and the Pennsylvania Department of Environmental Protection (PA DEP). Subsequent funding was from a grant from the Maritime Exchange. The EWS has been in continuous operation since its inauguration and has undergone multiple upgrades. The EWS monitors source waters in the Delaware River and Schuylkill River basins — the total watershed area for the source waters for the Philadelphia Water Department (PWD) is approximately 10,000 square miles. At present, the Delaware Valley EWS has more than 325 system users from Pennsylvania, Delaware and New Jersey. The EWS is maintained through contributions from 13 Pennsylvania water suppliers, four New Jersey water suppliers and 14 industrial water users/dischargers. The system is owned and operated by PWD, though other users can influence the operation and development of the system. The Delaware River Basin Commission (DRBC) collects fees on behalf of PWD for system maintenance purposes. The primary goal of the EWS is to support existing notification protocols in place to protect the drinking water supply for more than three million people. The type of notification (email or phone call) and the notification recipients depend upon the perceived severity of the incident. Additional benefits of the EWS are that it provides a secure forum for data and information sharing.

2.3.3.1 *EWS Specifics*

Components of the Delaware Valley EWS include 88 USGS gauge stations linked to the system, four remote terminal units (RTUs) connected to the water quality monitors and analytical tools. Monitoring is conducted on the Neshaminy Creek (at an Aqua Pennsylvania drinking water plant), the Schuylkill River and the Delaware River. Temperature, pH, flow, DO and conductivity are monitored at each location and data are collected at 15-minute intervals. The system previously included a fish monitor, but it was removed since it was difficult to maintain. Additional water quality data available for the Delaware River include monitoring data, from PWD and American Water treatment plants, and USGS water quality data.

Analytical tools in the EWS include a time-of-travel model and a tidal model. The time of travel model draws data from USGS gauge stations and has been used in spill tracking. The tidal modal is a critical component of the system because the zone of tidal influence of the Delaware River extends above drinking water treatment plant intakes.

During emergency response, the EWS provides data to system partners who make decisions regarding their own operations. At present, the EWS does not include event detection. Emergency response roles of the EWS are to facilitate communication for entities spanning a large geographic area and to provide a redundant path for communication.

Data are managed through a web page accessible by system users. When a user enters an incident into the system, a “code red” is issued and users are notified. Users determine if the incident/spill that they are reporting is either a low or high-level incident based on their judgement. Both low and high-level incidents generate an email to system users. High-level incidents also generate telephone calls. The system does not conduct downstream notification, though this feature has been requested. Paying members, regulatory agencies, Local Emergency Planning Committees (LEPCs) and the USCG have access to the Delaware EWS website.

2.3.3.2 *Prior Experience and Future Development*

The Delaware Valley EWS has detected or reported more than 500 incidents. Those include:

- A coal fly ash spill in an upper part of the watershed of 100 million gallons in 2007
- Numerous transportation accidents
- An industrial fire with runoff potential
- A crude oil spill of approximately 275,000 gallons in 2004
- A cyanide chloride compound discharged after wastewater treatment

Following the cyanide chloride discharge, drinking water treatment plant intakes along the flow path were closed and the EWS was used to facilitate communication during the response.

The Delaware Valley EWS is expected to continue operation for the foreseeable future and is considering expansion. Water suppliers operating downstream of the current coverage area (e.g., on the Brandywine Creek and Christina River in Delaware) are interested in joining. The system currently has no plans to include public reporting of suspected incidents or the capability for the public to download and analyze data. This decision was taken to ensure data remain secure, confidential and accurate. At present, data sharing requests are submitted by email and considered.

Research gaps and concerns identified by the Delaware EWS include the need for data analysis tools and for developing stronger linkages between water supplier source water protection efforts and local emergency planning. The data analysis tools would be used for event detection and for improved use of water quality data. A significant concern about data analysis tools is the likelihood of a high frequency of false positive assessments.

2.3.4 River Dee EWS

The River Dee EWS is overseen by United Utilities, a private company that serves as water supplier and wastewater manager and that has about seven million customers. In general, the EWS is intended to facilitate pollution risk management on the River Dee., and was formed in response to a large spill of chlorinated phenols that occurred in the mid-1980s. The spill impacted about two million people in north Wales and northwest England. Contaminated water entered the drinking water treatment plants and was detected in finished water. An inquiry of the incident recommended improved coordination among agencies to better manage the risk.

At its inception in 1984, the EWS was administered as a joint operation between the water companies and government organizations. Water companies contributed both staff and facilities. The EWS has been continuously operated since 1985. Laboratory analyses, sampling and online monitoring are conducted by a contractor. Originally four water companies participated in the EWS, but two of the original companies merged, and, thus, three companies are currently taking water from the River Dee. The Welsh regulators have the lead for the system. Two regulating agencies contributed financially at the onset of the effort, and currently provide in-kind support. The system is maintained financially by payment based on the amount of water taken from the river by each utility.

2.3.4.1 *EWS Specifics*

The River Dee EWS includes water quality monitoring (online and grab sampling), centralized data management and coordination and communication with water utilities and regulators. Monitoring includes three online water quality stations operating 24 hours per day, grab sampling at eight locations along the river system and laboratory analysis of grab samples within 6 hour or less. Online monitoring locations (Manley Hall, Poulton and Huntington) were chosen based upon the location along the river system and the proximity to treatment plants and the EWS laboratory. Results of laboratory analyses are reported to a quality control officer and regulators (Natural Resources Wales). When a pollution incident is declared, alarm notices are circulated among regulators and water companies. EWS laboratories have chemists/analysts who are engaged in analyzing follow-on sampling.

Online monitoring includes standard water quality parameters (e.g., DO, conductivity, pH, and temperature); two online monitoring locations employ online volatile organic compound (VOC) monitors (purge and trap GC). Six of the eight grab sample locations are along the River Dee main stem, while the remaining two are located on important tributaries. Grab samples are collected and analyzed twice per day. Routine sampling and analysis for phenols and other target compounds is conducted at one of the monitoring locations. The EWS employed fish monitoring in the early days of operation. However, the fish were generally stressed in all water quality conditions and, thus, the fish could not distinguish between pollution incidents and background stressors. Other biomonitoring technology was also piloted and abandoned because of performance or operational problems.

All online monitoring stations are linked via a commercial software product. The software can generate alarms based on set points, trends and interruption in signal/communication. Alarms can be based on the excursion of a single observation outside control limits. In routine online monitoring and reporting, water quality data are recorded each 15 minutes and individual data are retained for 48 hours. Data older than 48 hours are aggregated in daily minimum, maximum and median values, and then individual data are discarded. Each 12 months daily median, minimum and maximum values are summarized in a report to the drinking water company and other stakeholders.

2.3.4.2 *Prior Experience and Future Development*

The River Dee system meets the regulator goals of addressing water quality problems in catchments rather than via addition of expensive treatment, which further supports the continued operation of the River Dee EWS.

Early operation of the EWS resulted in numerous alarms, hundreds per month. These alarms were reduced significantly by filtering the samples prior to the GC analysis. Per the operators, about eight alarms occur per month from the intake protection system presently. The main detected incidents are from ammonia (tracked to sewage plant discharges to the river), DO swings (often diurnal) and nitrate alarms. At present, roughly half of the monthly alarms are genuine, and are followed up by human investigation. For example, an ammonia alarm investigation might involve determination of concentrations of caffeine, cholesterol or other indicators of sewage. Because the system has been operating for decades and with consistent staffing, analysts have become experienced and adept at investigating alarms and assessing whether they are genuine.

Future considerations for the River Dee EWS include adding optical DO monitors and other optical sensors. Interest in optical sensors is partly driven by the inaccuracy of ion selective electrodes and operational problems with colorimetric methods. Research gaps identified by the River Dee EWS include practical and accurate detection of inorganics.

2.3.5 West Virginia American Water (WVAW)Utility

In response to the 2014 Freedom Industries MCHM spill on the Elk River, the West Virginia legislature requires public water systems, providing water to 100,000 customers or more, to monitor source waters for key classes of contaminants. The West Virginia American Water (WVAW) utility opted to implement source water monitoring at all of its eight surface water plants in West Virginia, even though only one plant serves more than 100,000 people. The rule requiring monitoring is not specific regarding the classes of contaminants that should be monitored or the details of monitoring (e.g., instruments, frequency, performance objectives) required. In response to the monitoring requirement and to augment public health protection and incident response, the WVAW utility designed, fabricated and tested monitoring panels; installed panels at each of its treatment plants; established remote communication to the panels; connected data to an information system (with event detection capabilities); and established procedures for maintaining instruments and monitoring data. The panels included the online monitoring instruments. Stakeholders of the system include WVAW utility and regulators. The utility funds the entire cost of the system.

2.3.5.1 *EWS Specifics*

The WVAW EWS includes online monitoring, centralized data management, event detection for water quality changes and instrument performance notifications. Monitoring instruments have been operational for roughly one year. Monitoring is conducted on raw water from each of eight water treatment plants. Online monitoring parameters include dissolved organic carbon (DOC), pH, conductivity, oxidation-reduction potential (ORP), DO, temperature and turbidity. The precise location of monitors is different for each plant, since the locations were each chosen based primarily on logistical considerations, such as electricity and communication. For some plants, water is sampled directly from the raw water pumps. Travel time from the monitoring location to the treatment plant ranges from minutes to hours, depending on the plant. Grab sampling data are also collected for each plant raw water. Other data used for evaluation of water quality data and event detection include:

- Streamflow and precipitation data are accessed from external sources
- ORSANCO notifications of spills and incidents
- Additional water quality data from the River Alert Information Network (RAIN) system (WVAW utility is a member utility)
- Customer calls
- Gas chromatography – mass spectrometry (GC-MS) analyses conducted at two treatment plants

Water quality monitors are connected to data loggers (at each site) and access to data on the data loggers is via cell modem or Ethernet cable, depending on the availability of service at the location. Water quality data are maintained via cloud computing and are accessed by WVAW staff via a commercial web-based data management and analysis tool. At present, data can be accessed by the WVAW source water protection manager, water quality managers, plant operators and key staff. Data are analyzed by the Detector event detection software tool (http://www.mindset-tools.com/?page=detector) (Decision Makers Ltd., Boynton Beach, FL). Event detection has been underway for less than six months and a full review of results is not yet available. Detection of incidents by Detector software or by other analyses would result in confirmatory laboratory analysis followed by appropriate communication within WVAW, with regulators and with the general public (if merited).

2.3.5.2 *Prior Experience and Future Development*

The WVAW EWS has been operational for roughly one year and is still under development. A significant challenge to the system is determining which parameters need to be monitored so as to target the contaminants of greatest concern at each of the individual treatment plants. Other sensors might be added based on specific challenges at each plant. For example, an online algae monitor has been deployed at a plant that has its intake is on the Ohio River. Additional monitoring locations upstream of intakes are also under consideration, though practical challenges such as access to communications and power and vandalism must be overcome. One specific developmental goal is to achieve more consistent system operation. Consistent operation will require refining instrument operations and maintenance protocols and will require addressing vulnerabilities in the data communication pathway.

An additional goal is improving data analysis and interpretation. At present, strong connection between the water quality parameters that can be monitored and the contaminants present in the water near the drinking water intakes has not been established. Because WVAW utility is in the early stages of implementation of event detection, experience is required for better interpretation of alarms and for distinguishing false alarms from consequential water quality changes.

3.0 Sensor and Monitoring Technologies

Sensors and monitors are key components of an EWS as a mechanism for detecting the presence of potential contaminants. In this chapter, the general state of the science of sensor and monitoring technologies is presented. The design of monitoring networks for use in an EWS including the selection of technology and the siting of monitors are also discussed.

3.1 Background

Gullick et al. (2003) expanded on a review conducted by an ILSI working group (Brosnan, 1999) to develop a table of monitoring technologies for use in a source water EWS. The resulting technologies available when Gullick et al. (2003) conducted their study are presented in Table 2. The table shows instruments in three cost ranges (low-, medium- and high-cost) for measurement of classes or groups of threats (contaminants). Negative and positive aspects of each technology are outlined.

In Table 2, selectivity is noted as a negative for some technologies because the authors assessed that technologies detecting a broad range of contaminants were preferable to more selective technologies because any contaminant could be present in source water. An alternative viewpoint is that, for a particular source water intake, identifying contaminants that are more likely to threaten the water supply and selectively detecting contaminant levels associated with harmful levels of exposure, could be appropriate choices for an EWS. The connection between sensor choice and exposure was also made by Brosnan (1999), who noted that treatment-plant managers considered the top threats to their water supplies to be pollutants from oil and petrochemical spills, agricultural runoff, and untreated sewage. Many of the technologies listed in Table 2 are laboratory instruments used for detection of specific contaminants. Those instruments include inductively coupled plasma mass spectrometry (ICP-MS) for specific and sensitive detection of metals, liquid chromatography and liquid chromatography–mass spectrometry (LC and LC-MS) for specific detection of polar organic compounds, GC (including purge and trap GC) and gas chromatography-mass spectrometry (GC and GC-MS) for detection of volatile organics, ion chromatography (IC) for detection of ionic contaminants, and atomic absorption spectroscopy (AAS) for detection of metals.

Table 2. Select Approaches for Detecting Chemical and Radiological Threats to Drinking Water (modified from Brosnan, 1999; Gullick et al., 2003)

Threats	High-cost instruments ($100,000s)			Medium-cost instruments ($10,000s)			Low-cost instruments ($1000s)		
	Technologies	**Pros**	**Cons**	**Technologies**	**Pros**	**Cons**	**Technologies**	**Pros**	**Cons**
Ions (salts)				IC	Fast, broad, selective		Ion probes	Sensitive	Selective
Metals	ICP-MS	Fast, broad ID, sensitive	Staff, lab	AAS	Fast, sensitive	Staff, lab	Ion probes	Sensitive	Selective
				Polarography	Fast, fairly selective	Selective			
Polar organics	LC-MS	Broad ID	Staff, lab	LC	Broad ID	Staff, lab	UV		Lack of sensitivity
				TOC	Broad ID	Lack of sensitivity			
Non-polar organics	GC-MS	Broad ID	Staff, lab	LC	Broad ID	Staff, lab			
Volatiles, oils, hydrocarbons	GC-MS	Broad ID	Staff, lab	P&T – GC	Broad ID	Staff, lab	Smell bell	Fast	Human detectors
				GC	Broad ID	Staff, lab			
				Fluorescence (oil, HC)	Broad ID	Interferences			
Specific compounds	GC-MS, LC-MS	Broad ID	Staff, lab				Immunoassay (pesticides)	Fast, specific	Staff
Biotoxics				Biomonitors	Continuous, fast	Lack of specific ID			
Radiation				Tritium	Fast, specific	Not available online			
				Gamma detector	Fast, broad ID, available online	Lack of specific ID			
				Beta or alpha detector	Fast	Lack of specific ID, lab, evaporation step, not available online			

AAS, atomic absorption spectrometry (furnace or flame); Biomonitors, fish, daphnids, mussels, algal fluorescence, and luminescent bacteria; Broad ID, can monitor for many compounds simultaneously; Fast, not quantified in Gullick et al., 2003; GC, gas chromatography; HC, hydrocarbon; IC, ion chromatography; ICP-MS, inductively coupled plasma mass spectroscopy; ID, identification; LC, liquid chromatography; MS, mass spectrometry; P&T, purge and trap; Selective, monitors for a single compound; Smell bell, trained staff detect unusual odors in water sample; TOC, total organic carbon; UV, ultraviolet

Few technologies suitable for continuous, online monitoring are included in Table 2. As demonstrated in the response to the Elk River spill of MCHM, highly specific laboratory analyses can be an important part of a spill response (Rosen et al., 2014), though their expense and lack of mobility limit their use in routine, high-frequency monitoring.

Gullick et al. (2003) identified the following research and development needs focused on technology improvements:

- Continuous monitors for low levels of dissolved oil and petroleum products
- Rapid automated sensors for established and emerging pathogen and bio-warfare agents
- Simultaneous identification of multiple pathogens (combined biosensors)
- Improved sensor sensitivity
- Continuous, online and remote sensing monitors for a greater number of chemical parameters
- Electronic nose improvements
- Improved biological monitors
- Technology exchange between water supply and sensor development industries

As noted in the following section, significant progress has been made in addressing these needs since 2003, particularly in the identification and development of biosensors and the development of techniques and tools for improved source water assessment. In contrast, significant research needs remain with respect to more timely detection of microorganisms, acceptance of new or unfamiliar monitoring technologies, and development of smart sensors.

3.2 Emerging Technologies

Published studies report the emergence of numerous and diverse monitoring technologies in approximately the last decade. Since the reviews conducted in the early 2000s, two general types of online monitoring advances have dominated:

- Development and application of new technologies for detection of constituents of interest
- Modification of existing technologies to overcome features that limited their ability to be field-deployed

Many of the studies published over the last decade report performance of novel technologies in laboratories or other settings that might not reflect conditions representative of those in drinking source water. A partial list of realities of sensor deployment in source water includes fouling, interference by matrix constituents, power failures, accessibility difficulties, and degradation of critical sensor components. Many sensor developers have overcome these problems, indicating that they are tractable. However, until deployment problems are identified and addressed by both the sensor vendors and customers, emerging technologies will not be effective components of EWSs.

Van den Broeke et al. (2014) have developed a web-based compendium of online monitoring technologies and case studies illustrating their use in water settings (drinking water and wastewater). Among other uses, the compendium is intended to facilitate matching online sensor selection to specific operations and applications. The Online Water Quality Sensors and Monitors Compendium can be found at www.wqsmc.org. Data that can be retrieved from the compendium for a technology and a particular application include summaries, advantages, disadvantages, acquisition and operational costs, installation, operational and maintenance information, benefits, manufacturers and suppliers and use cases. Engineers have many considerations when selecting technology as a component of an EWS and those considerations extend well beyond the parameter(s) the technology measures.

This section provides an overview of emerging water quality monitoring technologies, with a focus on online monitoring technologies developed over the last decade. Online refers to technologies that automatically collect and communicate data, and includes technologies that monitor a flowing sample as well as those that collect and analyze discrete samples. The technologies reported in the literature vary widely in their state of development (from conceptual to commercialization), their focus on contaminants of relevance to drinking source water, and their potential for field deployment. A review of the literature indicates that the emerging monitoring technologies most relevant to drinking source water EWSs are biomonitors (monitors using the response of biological organisms to water constituents) and spectroscopic instruments (instruments sensing absorbance, transmittance, scattering/reflectance of electromagnetic radiation). These emerging technologies are the focus of this review. Readers are referred to recent reviews published by Banna et al. (2014) and O'Halloran et al. (2009) for additional information on other emerging technologies. Specific mention of sensor or vendor names in this section should not be construed as an endorsement or criticism of the technology or the vendor.

3.2.1 Routine Online Water Quality Monitoring

As noted by Storey et al. (2011), robust, commercially available technologies exist for many parameters routinely monitored in source water and treated water, with the notable exceptions of ammonia and fluoride. Methods for incorporating routine water quality data into EWSs are described in section 4.2. Wider application of commercially available instruments is governed by (i) their costs and benefits and (ii) whether these technologies can be used for specific contaminant detection.

Two recent reports (Hall and Szabo, 2010; Hall et al., 2009) described findings from the U.S. EPA sensor technology evaluations. Although the U.S. EPA studies focused on monitoring and detection in treated water, their findings are relevant to source water monitoring because many of the instruments evaluated could be used in both source and treated water and because the evaluations included operability and other technology features related to their practical use in a drinking water treatment environment. Evaluations indicated that free chlorine and total organic carbon (TOC) were the water quality parameters most sensitive to contaminant presence in distribution systems in which free chlorine was the secondary disinfectant. TOC is likely an important parameter for detecting contaminants in source water, too, although natural TOC variability in source water is much higher than that in treated water.

Several notable advances in monitoring of routine parameters have occurred since the early 2000s. For example, researchers have demonstrated the use of ultraviolet-visible (UV-vis) spectroscopy for monitoring suspended solids rather than turbidity (Lourenço et al., 2006; Reiger et al., 2004). Both studies note that turbidity, though familiar in the water treatment context, is a surrogate for suspended solids and subject to bias and interference. Another advantage to the use of UV-vis spectroscopy for determining suspended solids is the potential for replacing several probes (a turbidimeter and other water quality monitoring devices) with a single probe.

Banna et al. (2014) included differential pH sensors (one probe measures in a buffer and another in sample) and amperometric sensors among currently-available pH sensors tested by the U.S.

EPA. Emerging technologies for pH measurement include use of volume, optical and electrical changes in hydrogels, potentiometric pH sensors, ion-selective field-effect transistor pH sensors, and fiber-optic based pH sensors. Potential advantages of the alternative technologies include greater sensitivity, ability to miniaturize sensors, and greater longevity.

Miniaturization could facilitate easier deployment of sensors, particularly as components of multi-parameter probes (Gunatilaka et al., 2007). Miniaturization also facilitates sensor deployment in tighter or more difficult-to-access spaces such as building plumbing systems.

3.2.2 Biomonitoring

A comprehensive review of the many commercially available options for biomonitoring is found in a recent study by Kokkali and van Delft (2014). Biomonitoring refers to the use of living organisms that serve as indicators of water toxicity. Here, toxicity is specific to the organism(s) used in the monitor and does not refer to human toxicity. A wide diversity of organisms is used in commercially available biological monitors, or biomonitors. Kokkali and van Delft (2014) separated the organisms into the following broad categories:

- Microorganisms
- Enzyme-based detection and mammalian cells
- Invertebrates
- Fish
- Other organisms
- Multiple species

Commercially available versions of biomonitors include both laboratory and field-deployed monitors. All field-deployed biomonitors face two major challenges beyond those faced by other types of water quality monitors:

- Maintaining a population of viable organisms
- Mapping the behavior/response of biological organisms to water quality changes relevant in the drinking water production context

Storey et al. (2011) identified five commercially available biomonitors applicable to online source water monitoring. The organisms used in these biomonitors included bacteria, algae and fish. Limitations of commercially available biomonitors differ by technology and include slow response times, interference of constituents like chlorine with the organisms used for biomonitoring (i.e., false positives), low sensitivity of organisms to target analytes, lack of specificity (i.e., response to a broad range of contaminants rather than a targeted substance or group of contaminants), and operational challenges associated with maintaining the organisms.

Ren and Wang (2010) illustrated the challenges related to choice and maintenance of biological organisms in their study comparing biomonitors using the planktonic crustacean *Daphnia magna* and Japanese madaka or rice fish (*Oryzias latipes*). The organisms differed in their sensitivity to contaminants, the clarity with which their responses to stimulation could be measured and the duration of their survival without food. The authors found that neither species performed well for all metrics and suggested monitoring with both. Maradona et al. (2012) used responses of four species – *Daphnia magna and Hyalella azteca* (crustaceans), *Lumbriculus variegatus* (a freshwater worm) and *Pseudokirchneriella subcapitata* (a freshwater algae) – and principle component analysis of their responses to develop a library of contaminant-specific responses.

Tests with atrazine and tributyltin indicated their approach was promising and capable of detecting the target contaminants within two to four hours, which is likely sufficiently fast in the context of an EWS. Timescales relevant to spills on river systems are typically on the order of hours and determined by travel times from spill locations to drinking water plant intakes (though the travel time was much shorter in the 2014 Elk River spill of MCHM).

As noted in a review conducted by Girotti et al. (2008), many studies have evaluated bioluminescent bacteria as components of biomonitors. Bioluminescent bacteria offer advantages over other organisms including the potential for genetic modification, ease in measuring light output (the means for assessing response), rapid response to exposure to toxic compounds and response to a wide range of contaminants relevant to drinking water. Girotti et al. (2008) found studies on monitoring of cyanotoxins, arsenic, toluene, heavy metals, pesticides and polycyclic aromatic hydrocarbons (PAHs) in surface water. At least one biomonitor, Microtox® CTM, has been developed to work as an online instrument (http://www.modernwater-monitoring.com/product-microtox-ctm.html).

Although biomonitoring is often used for general water monitoring, some systems have been configured for detecting specific contaminants. For example, Zhang et al. (2012) developed an online biomonitor for the detection of carbamate pesticides. Their biomonitor employed medaka (*Oryzias latipes*). Dose-response experiments with *O. latipes* revealed a stepwise response to increasing doses of carbamate pesticides. The study did not report attempts to challenge the biomonitor with other toxicants and it is unclear how specific the monitor is for detection of carbamate pesticides.

Recent reviews of whole-cell biomonitoring (Eltzov et al., 2009) and monitoring with bioluminescent organisms (Woutersen et al., 2011) suggested that those two technologies have a high potential for being incorporated into future incident detection systems. These two types of biomonitoring systems can be configured as contaminant-specific systems and have the potential for online deployment (i.e., in field settings). Whole cells (or other biologically based materials) used as biosensors can be suspended, entrapped or bound to substrate. Based on a literature survey, Eltzov et al. (2009) reported application of whole-cell biosensors in a wide variety of water environments and for a wide variety of contaminants. Whole cell biosensors recognize (detect) contaminants via bio-recognition elements on cells that have been immobilized on the biosensing device.

In their review of biosensors based on bioluminescence, Woutersen et al. (2011) suggested that biosensors with genetically modified luminescent bacteria have the potential to provide real-time toxicity monitoring in water. Bioluminescent biosensors can provide rapid results that are easily measurable. Bioluminescence biosensors can signal the presence of a toxicant by “lights out” response (reduction in luminescence after exposure) or “lights on” response (increase in luminescence over background level) after exposure to a target contaminant. The lights-off versions typically use naturally occurring organisms and detect toxicity rather than the presence of a specific contaminant. The lights-on versions frequently rely on genetically modified organisms and they can detect a single contaminant or a group of related contaminants.

Woutersen et al. (2011) also reported the use of bioluminescence biosensors for many contaminants relevant to drinking source water early warning. Those contaminants included benzene, toluene, ethylbenzene xylene (BTEX) compounds, polychlorinated biphenyls (PCBs), phenols and metals (in particular, lead, mercury, iron and cadmium). Use of these biosensors as operational components of an EWS would require rigorous determination of their sensitivities, interferences and operational requirements.

3.2.3 Spectral Instruments

Many studies published in the past decade report novel applications of spectral instruments for monitoring water quality. This section provides a snapshot of the state of science in the use of spectral instruments for water quality monitoring by highlighting studies demonstrating online monitoring or with a focus on detection of parameters of greatest relevance to drinking water treatment and early warning.

Several commercially available sensors that utilize absorbance at wavelengths in the UV-vis range have been deployed for continuous water quality monitoring. Etheridge et al. (2013) noted that portable UV-vis spectrometers have been used for monitoring nitrate nitrogen (NO_3-N), DOC and total suspended solids (TSS). Examples of other studies reporting use of online or field-deployed UV-vis spectroscopy include monitoring nitrate+nitrite in wastewater (Drolc and Vrtovšek, 2010), ozone and assimilable organic carbon in partially treated drinking water (van den Broeke et al., 2008), and DOC and particulate organic carbon (POC) in surface water (Jeong et al., 2012).

As with other sensors, a significant hurdle that spectral (spectroscopic) instruments must overcome is operation in the field environment. Etheridge et al. (2013) noted that fouling via biological growth and chemical precipitation are significant problems that must be overcome for field deployment of any spectral sensor. In their study, the authors noted significant fouling and instrument performance degradation over periods of time as short as two weeks. In response, an antifouling system (limiting exposure of the probe to stream water in periods between measurements and automated rinses of lenses with clean water) was designed and implemented. The antifouling system enabled the use of the probe for extended periods with only minor drift in DOC measurements. Commercially available, field-deployable UV-vis spectrophotometers are sometimes equipped with fouling control. For example, the s::can spectro::lyser™ spectrometer can be equipped with automated air cleaning or brushes for physical cleaning (http://www.s-can.at/en/). Similarly, the Zaps LiquID™ Station spectrophotometer (http://www.zapstechnologies.com/the-liquid-station/) conducts periodic automatic cleaning of optical surfaces via pressurized air and clean water.

Analysis of data from UV-vis spectral instruments can be more complex than analysis of data from other instruments. Some instruments capture absorbance at many wavelengths over a wide wavelength range. Generally, absorbances must be corrected for suspended solids (which cause an apparent change in absorbance; Hu et al., 2016) and fouling, and data might be analyzed as corrected absorbances, first derivatives of corrected absorbances or second derivatives of corrected absorbances. Finally, constituents other than a target analyte can influence the absorbance spectrum. Partial least squares regression (PLSR) is the most common technique for matching spectral signals to target analytes (Chen et al., 2014; Korshin et al., 1997; Langergraber et al., 2003; Reiger et al., 2004; van den Broeke et al., 2008), though at least one study indicated that useful information can be drawn from direct use of raw spectral data (Vaillant et al., 2002). Prior to PLSR, absorbance data could be transformed to enhance the signal for constituents of concern. For example, Roccaro et al. (2015) found that log-transformation of absorbance data prior to analysis generated improved correlation of spectral data with trihalomethanes (THMs) and haloacetic acids (HAAs).

Some UV-vis spectral instruments are programmed with laboratory-generated profiles based on samples in water matrices that could differ from the matrix of the water being monitored. Because PLSR and other data reduction techniques are not widely used among environmental engineers, some users likely rely on factory calibration and profiles for their instruments. It is possible that the lack of calibration in the water being tested could result in suboptimal performance of an instrument.

In their report on the use of fluorescence spectroscopy for characterizing dissolved organic matter (DOM) in drinking source water, Carstea et al. (2014) contended that advantages of fluorescence spectroscopy over other water quality instruments were its high sensitivity, small required sample volume, low-to-no sample preparation requirements, and short measuring time. Disadvantages included difficulties in managing and analyzing the complex data stream some instruments produce and included interference via matrix constituents. Known interferences with fluorescence spectroscopy include inner filtering effect (absorbance of some emitted energy within the sample), oxidants and fluorescence quenching due to temperature, pH, and metal ions (Henderson et al., 2009).

Carstea et al. (2014) reviewed studies of water quality characterization via fluorescence spectroscopy and listed research studies in which researchers attempted to detect and characterize the water quality parameters including:

- Biochemical oxygen demand
- TOC
- Nitrogen and chemical oxygen demand
- DOM
- Diesel pollution
- Viral pathogens
- Pesticides
- Biological water quality

Fluorescence spectroscopy instruments can be designed to operate at one or several wavelengths or to produce a three-dimensional matrix of excitation-emission data (the excitation-emission matrix [EEM]) (Sanchez et al., 2014). Like absorbance spectra, EEMs require sophisticated analyses for interpretation, given their complexity and the fact that multiple substances can produce similar signals in the EEM. The most commonly reported technique for analyzing the EEM is parallel factor analysis (PARAFAC) (Guo et al., 2010; Johnstone et al., 2009; Sanchez, et al., 2014; Yang et al., 2015). Parallel factor analysis identifies the most important excitation and emission wavelengths, which can be used to indicate specific contaminants or to indicate water quality in lieu of analysis of the entire EEM.

The majority of recent studies reporting the use of fluorescence spectroscopy in drinking water applications were for characterizing and quantifying organic matter. The nature of organic matter in drinking source water is a key determinant of coagulation efficacy and the potential for disinfection byproduct (DBP) formation. Sanchez et al. (2014) developed analytical techniques for evaluating the 3-D EEM and for characterizing DOM changes along a treatment train in a drinking water treatment plant. In addition, the authors developed techniques to explore the removal of DOM in coagulation. Over a three-year period, the researchers collected pre- and post-coagulation samples, and characterized the DOM changes associated with coagulation. Although the study entailed grab sampling (rather than online monitoring), the study provided a proof-of-concept for continuous monitoring and analysis of the EEM. The study also demonstrated that fluorescence spectroscopy provided information for enhancing coagulation that is not provided by simple measurement of TOC/DOC.

Stedmon et al. (2011) determined that online fluorescence spectroscopy could be developed for early warning of sewage contamination of wells. Sewage was spiked into water samples corresponding to various levels of treatment and PARAFAC, a multi-way spectra decomposition method, was used to determine factors associated with the presence of sewage. A single excitation wavelength and two emission wavelengths appear sufficient for detecting sewage in that system. Reduction of the EEM to a smaller set of excitation and emission wavelengths allows development of a practical sensor for in situ monitoring and early warning of well contamination.

An alternative to using the entire EEM for water quality monitoring is monitoring of fluorescence at a single wavelength. According to Downing et al. (2012), instruments that measure chromophoric dissolved organic matter (CDOM) fluorescence at wavelengths of approximately 460 nm in response to excitation at approximately 370 nm have proven to be a highly sensitive and useful tool for elucidating spatial and temporal DOM variability. Sensors measuring the fraction of CDOM that fluoresces (i.e., fluorescent dissolved organic matter [FDOM]) are commercially available, simpler to use than analyzers using the full EEM, and increasingly used more in research settings. Downing et al. (2012) assessed the performance of four commercially available FDOM sensors in laboratory and field studies. The four instruments differed in performance, but all were susceptible to interference from color, suspended solids and temperature. These findings indicate that data from the instruments must be corrected for light scattering and temperature for accurate measurement of FDOM. Those corrections might require simultaneous deployment of turbidimeters (or other suspended solids monitors) and temperature probes.

Bridgeman et al. (2015) assessed the feasibility of fluorescence excitation at two sets of wavelengths for continuous detection of TOC and microorganisms. Assessments were conducted in a laboratory setting and using river water samples. Bridgeman et al. hypothesized that:

- Fluorescence emitted at 400–480 nm under excitation at 300–360 nm (fulvic-like fluorescence) is indicative of the presence of organic carbon (peak C)
- Fluorescence emitted at 340–370 nm under excitation at 220–240 nm or 270–280 nm (tryptophan-like fluorescence) is indicative of microbial activity (peak T)

At low TOC concentration (less than 25 mg/L), a linear relationship was observed between peak C fluorescence and TOC. At higher TOC concentrations, the relationship became nonlinear, but remained monotonic, though characterized by significant scatter in the data. Correlation between measures of biological water quality (heterotrophic plate count, flow cytometer counts, counts of individual species of bacteria) and peak T were not as good as correlation of TOC with peak C. The experimental design might have been responsible for the ambiguous results for microorganisms; counts of microorganisms in the samples were not precisely established or controlled in experiments. In summary, Bridgeman et al. (2015) demonstrated the potential for fluorescence field instruments to monitor organic carbon, though it is critical to account for interferences and understand the relationship between peak C and TOC at relatively high TOC concentrations.

By examining the full excitation-emission spectrum, Zhou et al. (2016) determined that excitation at 275 nm and emission at 342 nm correlated well with concentration of tryptophan-like proteinous fraction of CDOM in a surface water. The tryptophan-like fraction can be indicative of sewage in the surface water. The authors hypothesized that variations in CDOM from sewage inputs to a lake could be distinguished from variations due to hydrologic processes. Distinguishing an incident (e.g., a sewage overflow) from other natural variations (e.g., those driven by rainfall and runoff) is a significant challenge in source water monitoring for early warning. Zhou et al. (2016) used PARAFAC analysis to identify the fluorescence signature providing the best indication of sewage inputs to a lake and to identify point source pollution inputs to the lake.

Li et al. (2016) examined the full EEM and determined that excitation at a single wavelength - 280 nm - could excite humic-like and protein-like emission. The humic-like fraction was subsequently found to correlate well with both THM and HAA yields. This finding is similar to that of Johnstone et al. (2009) who used PARAFAC to deduce EEM factors that correlated well with DBP formation potential and DBP production. Li et al.'s (2016) good correlation with DBP formation potential using a single wavelength for excitation wavelength and a single emission wavelength indicates potential for development of a simplified online DBP precursor sensor.

3.2.4 Cyanobacteria and Cyanotoxins Monitoring

A specific type of contaminant incident that has emerged in recent years as a significant challenge to the drinking water community is the presence of HABs. Recent incidents impacting the operation of treatment plants, such as the City of Toledo operation, and forecasts that climate change and anthropogenic nutrient loading could lead to more frequent and widespread HABs with the potential for greater production of cyanotoxins emphasize the significance of this challenge (Gehringer and Wannicke, 2014; Paerl and Huisman, 2009). The literature review uncovered numerous reports of early warning activities focused on HABs, highlighting their importance. For this reason, a more thorough review of these activities is described here.

HABs are caused by the growth of cyanobacteria, which are sometimes referred to as blue-green algae, although they are bacteria, and not algae. Some cyanobacteria produce cyanotoxins depending on environmental factors such as nutrient limitation. Several cyanotoxins have varying health impacts including the nervous system, liver and skin toxicity. The most studied toxins are microcystin, cylindrospermopsin, anatoxin-a and saxitoxin. Microcystin is the most frequently detected of the cyanotoxins in U.S. lakes and reservoirs (Graham et al., 2009, 2010; Loftin, 2008).

An increase in cyanotoxin-producing algal blooms in the United States has been linked with two major factors. The first is the eutrophication of freshwater sources, caused by nutrients, mainly nitrogen and phosphorus (Dolman et al., 2012; Yuan et al., 2014). The other is the impact of climate change, which is producing a warming trend in the majority of lakes (O'Reilly et al., 2015). Warming trends could lead to increases in HABs, and significant implications for the monitoring and management of bloom incidents (Delpla et al., 2009; Paerl and Paul, 2012).

Drinking water treatment plants can remove cyanobacteria, and treat cyanotoxins to some extent. The limited data available show that there is a very low percentage of treated drinking water with cyanotoxin detections (Carmichael, 2000). The treated water detections that are documented have made an impact on utilities and regulators. In August 2014, the City of Toledo, Ohio issued a Do Not Drink/Do Not Boil order that stemmed from a microcystin detection in the treated water above 1 μg/L for microcystin, which at the time, was the threshold established by Ohio EPA (Ohio Environmental Protection Agency, 2014). In the summer of 2015, the U.S. EPA issued Health Advisories for microcystins and cylindrospermopsin largely in response to the Toledo incident.

The combination of increasing blooms (both size and frequency) and current attention to cyanotoxins in drinking water emphasizes the need for early warning and rapid detection methods for cyanobacteria. Historic monitoring for cyanobacteria and algae has been conducted by collection of grab samples and enumeration and identification with microscopes. This time consuming and laborious process is completely unsuited for the kind of rapid detection that is needed. Three categories of early warning and rapid detection are discussed in the following sections: remote sensing, modeling and monitoring.

3.2.4.1 *Remote Sensing*

Remote sensing has been proposed and developed as a component of HAB early warning. Remote sensing offers advantages over water quality sampling including collection of data over wide areas and with high frequency relative to traditional water quality sample collection and analysis. Thus, remote sensing could be used in conjunction with traditional water quality analysis and other data collection and analysis for early detection of HAB occurrence and improved drinking water operation response.

Seven satellites with instrumentation suitable for chlorophyll-a, or cyanobacteria detection, are in orbit now (Trescott, 2012). Remote sensing involves determining absorption and/or reflection at wavelengths specific to a particular water quality constituent. Chlorophyll-a has distinct absorbance peaks (433 nm and 686 nm) and reflectance peaks (550 nm and 690-700 nm) in the visible light portion of the spectrum (Cracknell et al., 2001).

Remote sensing poses challenges to widespread use for cyanobacteria early warning:

- For lakes and reservoirs, water quality data alone are not sufficient for early warning to manage HAB risks to drinking water plants, since risks to drinking water intakes depend on unique characteristics of water bodies, particularly their size, and the practicality of water quality monitoring with a limited number of sensors.
- Cyanobacteria blooms can occur on rivers (in addition to lakes and reservoirs), which are flowing water bodies and are subject to obscuring by tree canopies.
- Models and analyses connecting water quality and other data used in early warning need to be developed and validated to account for the unique characteristics of the water body that influence the absorbance or reflection of the light.
- Cloud cover can obscure the satellite images.
- Due to the flyover schedule, the satellites which are used for remote sensing are not always present above a given location. Satellites can have a fly over schedule as little as 1 to 2 days, or as many as 16 days (Trescott, 2012).
- The detection of a bloom incident is possible at high biovolume (mass of microorganisms) levels but is not accurate at the lower levels required for managing risks associated with drinking water sources.
- The growth of cyanobacteria does not necessarily mean that toxins are being produced, and the remote sensing technology cannot determine if cyanotoxins are present (Freeman, 2011).

The National Oceanic and Atmospheric Administration (NOAA) has two active HAB prediction demonstration projects (NOAA, 2013). In the Gulf of Maine, NOAA has been forecasting red tide. In the Great Lakes, the Great Lakes program has a fully developed prediction network (Freeman, 2011; NOAA GLERL, 2016), which focuses its efforts on Lake Erie, Saginaw Bay and Lake Huron.

Several other projects were short-term in nature and did not have fully developed EWSs, or were centered on oceanic HAB prediction (Hunter et al., 2008; Klemas, 2012; Kudela et al., 2015; Kutser et al., 2006; Lunetta et al., 2015; Matthews et al., 2010; Simis et al., 2005; Trescott, 2012). NOAA has three additional research projects using remote sensing for HAB forecasting in coastal locations (NOAA, 2013).

3.2.4.2 *Models for Predicting HAB Blooms and Transport*

As described in section 5.2, models (analytical or computer simulations) can be a useful component of an EWS by forecasting or integrating water quality data. Inputs to models can be data that indicate the extent of blooms (e.g., spectrally-resolved satellite imagery), grab sample results (e.g., chlorophyll *a* concentration, cyanobacteria concentration or cyanotoxins identity and concentration), hydrologic and atmospheric data (e.g., wind speed and water temperature), and other water quality data related to bloom occurrence (e.g., pH and DO). Lake Erie is the focus of two physical models that have been developed for predicting the occurrence, fate and transport of algae blooms (Francy et al., 2015; Wynne et al., 2013). Wynne et al. (2013) developed their model for algal bloom early detection for Lake Erie. Their model used satellite imagery as a key input and determined that blooms were predicted by water temperature and wind speed. Francy et al. (2015) monitored for concentrations of cyanobacteria by molecular methods, for algal pigments such as chlorophyll and phycocyanin by using optical sensors and for a number of other water quality parameters that served as inputs to models for various sites on Lake Erie and some inland lakes. These models demonstrate the potential for successful development of EWS for drinking source water for incidents that are of growing concern. They also demonstrate that such systems (and their underlying models) can be data intensive and require specialized expertise for their successful use.

3.2.4.3 *Monitoring Equipment*

Online fluorometer analyzers can be used to detect cyanobacteria by measuring the fluorescence of the phycocyanin pigments (the most specific indicator of cyanobacteria) or chlorophyll-a (an indicator of algae). The online analyzers are capable of detecting cyanobacterial concentrations as low as 150 cells/mL. Reported uses of online fluorometers for cyanobacteria detection are summarized in Table 3. Zamyadi et al. (2012) conducted a partial survey of studies on excitation and emission wavelengths used in studies of cyanobacteria and phytoplankton monitoring. The authors reported a wide range in excitation wavelengths (430-625 nm) and a much narrower range in emission wavelengths (655-690 nm). A principle concern in the study conducted by Zamyadi et al. (2012) was the utility of fluorescence probes for *in vivo* monitoring of phycocyanin and chlorophyll-a, and the use of the fluorescence probes within an EWS. The authors determined that online fluorescence spectroscopy improved early warning capabilities over monitoring of other physicochemical properties alone and improved the ability to distinguish cyanobacterial blooms from other algae blooms. The fluorescence spectroscopic measurements in the study did not correlate with microcystin concentration.

Polymerase chain reaction (PCR) can be used to detect cyanobacterial deoxyribonucleic acid (DNA) that has the potential to produce toxins. Reviews of the use of molecular methods in detection and management of cyanobacteria have been published by Moreira et al. (2014) and Srivastava et al. (2013). Studies reporting the use of PCR for cyanobacteria detection or detection of toxic cyanobacteria are presented in Table 4. For example, the microcystin synthetase gene cluster is an indicator of the potential for microcystin production (Francy et al., 2015). A complication related to use of PCR for detection of toxin-producing cyanobacteria is that several genera of cyanobacteria can have this gene cluster, but it can also be absent in those genera. Identification by microscopy can identify the cyanobacteria genera, but cannot determine if the cyanobacteria is a toxic strain. The ability to differentiate a toxic bloom from a non-toxic bloom is one advantage of molecular methods over microscopy and online analyzers. At present, commercially-available PCR-based monitors capable of continuous monitoring are not available.

Table 3. Online Sensor for Cyanobacteria Literature Summary

Location	Finding	References
Ruhr Basin, Germany	An online fluorometer is used for chlorophyll-a detection.	Bode and Nusch (1999)
Murray and Lower Darling Rivers, Australia	The project examined whether the *in situ* quantification of phycocyanin by fluorometry could be used to determine the abundance of cyanobacteria present. Abundance was measured in the laboratory as biovolume from samples collected at the same time as the phycocyanin measurements. The study found a strong positive relationship between the two measurements. However, it was found that the use of *in situ* phycocyanin fluorometry was not effective in turbid water higher than 50 Nephelometric turbidity units (NTU) as this produced false-positive readings for phycocyanin.	Bowling et al. (2013)
Maine et Loire, France	Four online analyzers were tested. Although the results were not as reliable as laboratory tests the information was very useful for making quick adjustments to plant operations.	Cagnard et al. (2006)
Taiwan	Results showed that chlorophyll-*a*, turbidity and the colonial status of the cyanobacteria significantly interfered with the measurement of phycocyanin fluorescence. Models were developed to compensate for the effect of chlorophyll-*a*, turbidity and colony size on the measurement. The models were successfully used to correct phycocyanin probe data collected from several reservoirs in Taiwan to establish good correlation between measurements made using the phycocyanin probe and microscopic cell counts.	Chang et al. (2012)
Poland	Statistically significant correlation between cyanobacterial biovolume and fluorometer readings and very strong correlation between chlorophyll-a and fluorometer readings was found.	Izydorczyk et al. (2009, 2005)
Hong Kong	Online fluorescence monitoring is used in conjunction with other parameters to send alarms when a bloom is occurring along the coast so that additional physical samples can be collected.	Lee et al. (2005)
Canada	A significant relationship between phycocyanin fluorescence and cyanobacterial biovolume was found when the growth was dominated by microcystin producing cyanobacteria.	McQuaid et al. (2011)
North and South Carolina	A multiple-fixed-wavelength spectral fluorometer was used to measure chlorophyll-a, and correlated with laboratory measurements. The analyzer	Richardson et al. (2010)

Location	Finding	References
	appears to be a useful tool for early warning of harmful algal blooms.	
Canada	*In vivo* probes were used to trace the increase in floating cells over the clarifier, a robust sign of malfunction of the coagulation–sedimentation process. Pre-emptive treatment adjustments, based on *in vivo* probe monitoring, resulted in successful removal of cyanobacterial cells. The field results on validation of the probes with cyanobacterial bloom samples showed that the probe responses are highly linear and can be used to trigger alerts to take action.	Zamyadi et al. (2014)

References are listed at the end of the report.

Table 4. Molecular Method Application for Cyanobacteria Detection

Location	Finding	References
Malpas Dam, New England region of Australia	Showed that bloom components can be identified and monitored for toxigenicity by PCR more effectively than by other methods such as microscopy and mouse bioassay.	Baker et al. (2002)
Lake Erie, U.S.	Researchers developed models for predicting microcystin concentration. Models used 14 physical variables including cyanobacteria DNA, cyanobacteria RNA, cyanobacterial biovolume (mass associated with cyanobacteria) and abundance (number of cyanobacteria per volume of water). The models were able to accurately predict microcystin concentration, however, different factors were important at each site.	Francy and Stelzer (2014) and Francy et al. (2015)
Guadarrama River, Spain	Sequencing of 16S rRNA gene fragments produced identification of cyanobacteria consistent with microscopic observations. The 16S rRNA gene is considered the best target for the phylogenetic classification of cyanobacteria and investigating the discrepancy natural communities of cyanobacteria (Nübel et al., 1997).	Loza et al. (2013)
Lake Erie, U.S.	Microcystis species could be detected using the qPCR method.	Wilhelm et al. (2007)

References are listed at the end of the report.
PCR, polymerase chain reaction.

3.3 Design and Siting of Monitoring Networks for Source Water EWSs

Monitoring networks are key elements of a source water EWS. Design of such a network includes the selection of technology and the siting of monitors. Grayman (2008) lists the following criteria for the selection of monitoring technology:

- Cost (capital and operational)
- Spectrum (broad spectrum or specific constituent)
- Sensitivity
- Operational and maintenance requirements
- Environmental requirements (power, shelter)
- Sampling frequency
- Communications requirements

Many studies have addressed the design and siting of monitors within distribution systems. Murray et al. (2010) provided a summary of the literature in that field with emphasis on U.S. EPA's Threat Ensemble Vulnerability Assessment – Sensor Placement Optimization Tool (TEVA-SPOT) software. Hart and Murray (2010) discuss sensor placement strategies for the design of a distribution system contamination warning system. Though some of the procedures and characteristics related to monitoring technology developed for distribution system contamination warning systems are relevant to source water EWSs, the methodologies and algorithms related to siting monitors in distribution systems are not transferrable to source waters because of the vast differences between distribution system and surface water configurations.

Strobl and Robillard (2008) reviewed available methods for designing water quality monitoring networks for surface freshwaters including both monitor locations and monitoring frequency. However, the methods described in this paper emphasize monitoring networks that are used for assessing long-term water quality rather than for detecting infrequent contamination and spill incidents. Only a limited number of studies have been related to siting monitors in natural source water supplies for detection of sporadic contamination incidents. Grayman and Males (2002) described a risk-based methodology using a Monte Carlo simulation model for siting monitors that accounts for the probability of spills, behavior of monitoring equipment, variable hydrology and the probability of obtaining information about spills independent of a monitoring system. This model was applied to a 200-mile industrialized stretch of the Ohio River to simulate the effectiveness of alternative monitoring locations as part of an EWS. Several researchers have applied optimization algorithms for addressing siting of monitors on rivers to detect spills. Park et al. (2006), Ouyang et al. (2008) and Telci et al. (2009) used genetic algorithms, and Park et al. (2010) used an optimization via simulation algorithm with a penalized objective function to address the water quality monitoring siting problem. In actual practice, monitors are generally placed in a more ad hoc manner based on "covering" stretches of rivers that are most susceptible to spill incidents, in the vicinity of important water intakes and locations where the monitors can be easily serviced and managed.

4.0 Statistical Event Detection Methodologies

Online sensors can provide large amounts of water quality data in real-time. In order to be effective as part of an EWS, statistical mechanisms for quickly evaluating the data and identifying measurements that might indicate a contamination incident are required. Such mechanisms are referred to as *event detection algorithms* and can take many different mathematical forms. Available event detection methods are reviewed in this chapter.

4.1 Background

Earlier studies of event detection envisioned generation of alarms based on specific or general measures of water quality crossing thresholds selected based on human health risks or other measures (Gullick et al., 2003; U.S. EPA, 2005). For example, Gullick et al. (2003) envisioned an EWS with predetermined response thresholds. Response thresholds were envisioned as set water quality parameter levels, either absolute or with respect to a baseline, at which a response is initiated. Responses included confirmation procedures for verifying that excursions beyond thresholds were real, additional characterization of the incident, characterization of the incident and assorted response actions. Suggested factors to consider when establishing thresholds included:

- Historical patterns of water quality
- Actual or perceived threat associated with levels of a contaminant or an incident
- Toxicity of the contaminant being measured
- Nature and size of the exposed population
- Ability of treatment processes to remove the contaminant
- Sensitivity and specificity of the monitoring method
- Type and severity of action that might be taken when a trigger level is exceeded

Reviews published in the 2000s also noted that thresholds and other parameters should be adjusted and optimized to minimize false alarms, but still detect credible contamination incidents (U.S. EPA, 2005). Maintaining a low incidence of false alarms is critical to protecting both public health and keeping the confidence of the public.

The U.S. EPA (2005) noted the potential for detection of specific contaminants using multiple water quality parameters. The authors envisioned a contaminant would be detected via a "signature" discerned from a characteristic pattern of changes in multiple physicochemical parameters. At the time of the U.S. EPA review, at least one monitoring technology company, Hach (Loveland, Colorado), had developed a methodology for detecting contaminants in treated water by integration of data from multiple water quality monitors. As noted below, both researchers and commercial concerns have continued development of multi-parameter sensors and data analysis for contaminant detection.

4.2 Integrating Data from Multiple Sensors

Che and Liu (2014) developed and evaluated a relatively straightforward technique for using multiple water quality measurements (pH, turbidity, conductivity, temperature, oxidation-reduction potential, UV-254, nitrate-nitrogen and phosphate) to detect specific contaminants (glyphosate, atrazine, lead nitrate and cadmium nitrate) in treated drinking water. Results of their study should be considered preliminary, since sample water was drawn from a tank with homogeneous water quality and presence of contaminants did not have to be distinguished from variations in background water quality. Detection of contaminants was based on correlation coefficients between pairs of water quality data within a number of time steps (window size). Under these idealized circumstances, Che and Liu (2014) detected the contaminants used in their study with a relatively short response time (i.e., time between introduction of the contaminant and detection of the contaminant) and observed a low rate of false positive observations (i.e., determining a contaminant was present when it was not). The choice of window size and thresholds influenced their proportion of true positive findings. A subsequent study by the same authors (Liu et al., 2015) extended the approach and based alarms on Euclidean distance of correlation indicators. The modified method outperformed two other techniques in correctly detecting actual changes in water quality, though like the former study, experimental work was not conducted in field conditions and with variable background water quality.

Han et al. (2014) were less successful in detecting specific contaminants using a multi-parameter sensor approach. The authors conducted their studies in a single-pass pipe loop and injected organic contaminants (ethylene glycol, 2-methyl-4-chlorophenoxyacetic acid, acetonitrile and dichloromethane), inorganic contaminants (aqua ammonia and copper sulfate) and simulated municipal sewage. The system tested was better able to detect nonvolatile organic contaminants than volatile contaminants and inorganic contaminants, but generally unable to positively identify any of the detected contaminants. Some of the poor performance noted in the study related to operational and design problems with the equipment. Those problems included clogging of instruments by particles and precipitates in the sample water and loss of volatile constituents in an instruments measuring TOC.

4.3 Event Detection Algorithm Studies

In the past decade, many studies reporting mathematical approaches for detecting incidents from water quality time series data have been published. Studies span the range of potential applications (rivers, lake and reservoirs, marine, stormwater, sewage collection, water and wastewater treatment, drinking water distribution) with the exception of building plumbing systems. This section overviews the state of the science and focuses on the two most reported approaches: artificial neural networks (ANNs) and analysis of receiver operating curves.

Two studies (Dawsey et al., 2006; Murray et al., 2011) report the use of Bayesian belief networks (BBNs) for distribution system contamination event detection. The BBN approach demonstrated in the studies entails use of a pipe network model (EPANET) to simulate contaminant injections at various points in a distribution system and characterization of the responses of sensors installed at various locations in the simulated distribution system. Potentially, a similar approach using stream network models could be used for event detection in source waters. The BBNs developed by Murray et al. (2011) successfully identified contaminant responses in observed experimental data, although the authors also found that the inclusion of data from unresponsive sensors in their analysis impaired their ability to identify contaminant responses.

Several studies have reported event detection algorithms based on ANNs. For example, Perelman et al. (2012) used ANNs to estimate the relationships between water quality parameters in a treated water distribution system and a Bayesian sequential analysis for estimating the probability of an incident. The authors demonstrated proof-of-concept using a simulated data set and suggested follow-on research to test, generalize and improve the method's performance.

Wu et al. (2014) conducted a review of the application of ANNs in the field of environmental and water resources modeling. The review was conducted to characterize ANN modeling practices and establish best practices (consistency in model development and assurance that models are sufficiently detailed). ANN model development and application was parsed into six steps:

- Input selection (with explicit treatment of significant and independence)
- Data splitting
- Model architecture selection
- Model structure selection
- Model calibration
- Model validation

A flowchart showing these steps as a part of a protocol for model development is presented in Figure 3. The authors conducted critical reviews of 81 published studies on the application of ANNs for analysis of water quality. Areas of application among the reviewed studies were lakes and reservoirs (19 studies), rivers (35), groundwater (9), stormwater (4), treatment (8) and distribution (7). In general, published studies reported similar model development and application processes. Model architecture selection was judged to be the strongest element of model development among the studies and input selections was the element requiring the most improvement. The authors made numerous recommendations for the ongoing development of ANN models for water quality data analysis, including greater focus on data independence in the input selection step, better documentation of the model calibration step, and improved quantification and reporting of uncertainty.

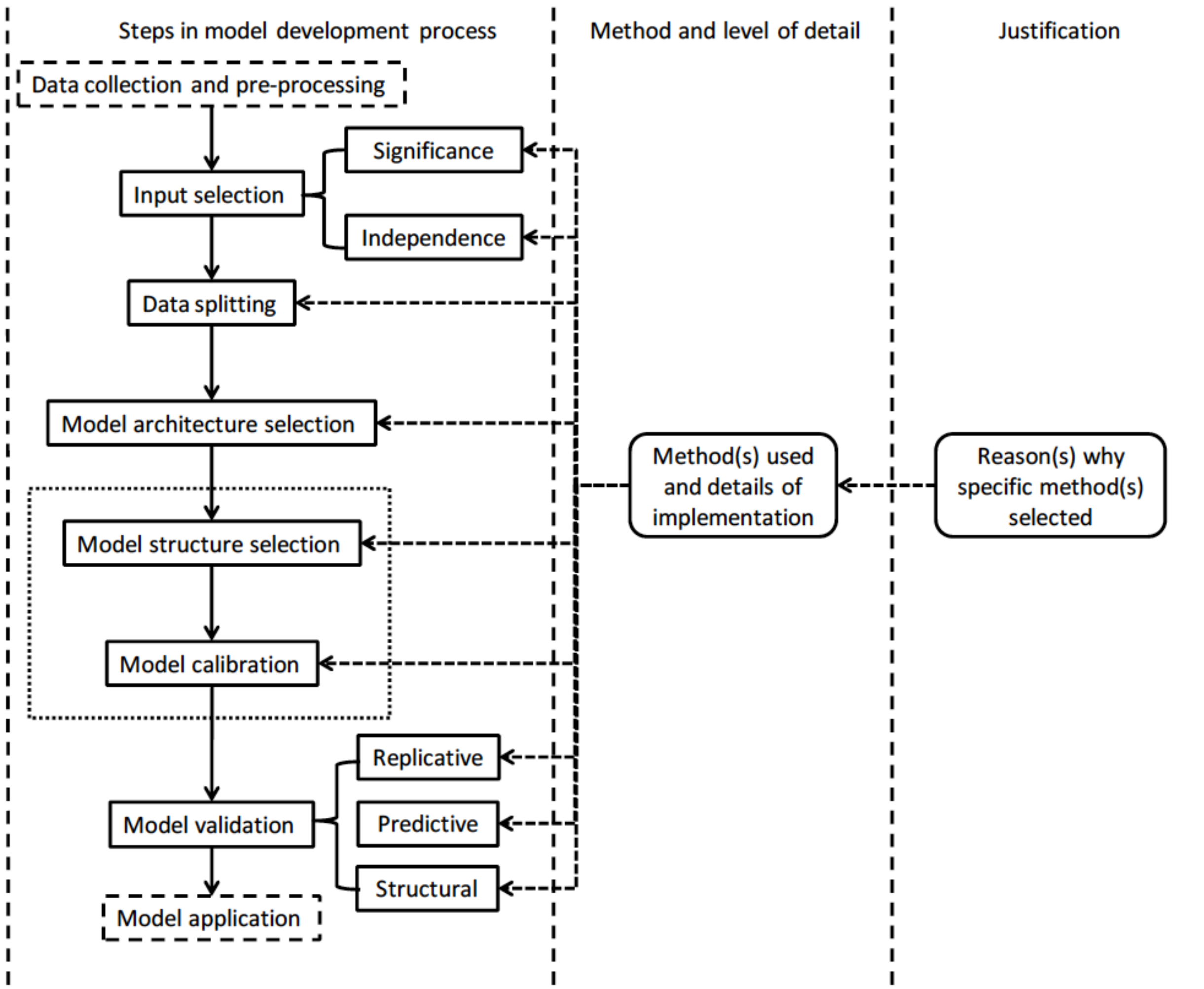

Figure 3. Proposed protocol for development and application of artificial neural network (ANN) models (from Wu et al., 2014).

Recently, Oliker and Ostfeld (2015) described inclusion of a pipe network hydraulic model as a component of an event detection technique. The first step in their event detection technique was the analysis of each data stream (time series of individual parameter and single locations) via a "minimum volume ellipsoid (MVE) classifier trained on identifying suspiciously exceptional measurements" as described in Oliker and Ostfeld (2014). Including network hydraulics and spatially dispersed sensors resulted in reduced false positive detection rate over event detection based on single sensors in analyses of a simulated data set. Results of this study hold promise for event detection including stream network hydraulics for source water event detection.

Several water quality event detection techniques have been included in the CANARY online water quality data management and event detection tool (McKenna et al., 2008; U.S. EPA, 2012). The algorithms within the CANARY event detection system are based on analysis of receiver operating characteristic (ROC) curves and include the following options:

- Linear prediction coefficient filter (LPCF)
- Multivariate nearest neighbor
- Set-point proximity algorithms

The inclusion of several options for event detection allows CANARY users the opportunity to base incidents on multiple algorithms (reducing the false positives and negatives) or to determine the algorithm that provides the most reliable event detection for a particular system or location.

Subsequent to developing CANARY, the U.S. EPA and Sandia National Laboratories developed and demonstrated techniques for incorporating operational data within distribution system event detection (Hart et al., 2011). Composite signals (water quality data and other relevant data such as operational status) can be used to set dynamic event detection set points or for false positive reduction (i.e., to avoid flagging data as incidents when they can be explained by known operations actions). Incorporation of operations data is important, since common operations such as tank emptying and filling can produce water quality signals that appear as incidents. An alternative approach to ensuring operations and routine water quality changes are not interpreted as real incidents was demonstrated by Zhao et al. (2015). In that study, patterns in historic data were recognized and used in interpretation of water quality data. The authors found that for the tests they performed, interpreting data in the light of routine patterns allowed more sensitive event detection as well as a reduction in the number of false positive incidents. An analogy can be drawn between water quality changes driven by operation of distribution systems and water quality driven by precipitation in source water. In both cases, an external stimulus known to the system operator causes a rapid, but expected water quality change.

5.0 Modeling as an Element of Early Warning Systems

Mathematical modeling of water quality in surface water dates back to pioneering work on the oxygen balance in the Ohio River (Streeter and Phelps, 1925). With the advent of digital computers, computer models were developed to simulate surface water quality (Thomann, 1963). Subsequently, extensive development and application of computer models to simulate surface water quality has occurred. Water quality modeling has been used for a variety of activities such as: development of discharge permits, waste load allocations, impact assessment of non-point sources and combined sewer overflows and, most relevant to EWSs, prediction of movement and impacts of transient spills.

5.1 Background

Grayman et al. (2001) presented an in-depth review of surface water models for use in EWSs. The following material is drawn directly from that report and serves as a review of the state of the science of modeling as an element of EWSs circa 2001.

- Spill models are a class of models that are used to trace the movement and fate of transient contaminants in receiving water. They are generally used in real-time or near real-time situations.
- Streams and rivers, lakes and reservoirs and the non-saline portions of estuaries are potential sources of drinking water and thus, are the surface water categories that can benefit most greatly from spill models as they apply to drinking water sources.
- Three basic components of any spill model include: a flow module, a water quality transport module and a fate module. The flow module describes the movement of the water; the water quality transport module describes the processes by which the contaminant concentration moves and changes due to the hydrodynamic forces; and the fate module describes the impacts of physical, chemical and biological processes on the form and concentration of the contaminant. These modules could be represented in separate models that are interconnected through input-output or might be integrated into a single model that represents the entire process.
- Flow models used in EWS modeling can be classified as: non-hydraulic methods, hydraulic methods for steady flows, unsteady flow models, lake and reservoir models and estuarine models. Each of these general methods has a potential place in spill models.
- Water quality transport models represent the movement of contaminants in the aquatic environment. Transport processes include the advective movement and the diffusive processes that spread the contaminant. Diffusive processes include both molecular diffusivity and turbulent diffusion. In many situations, models can be used that are simplifications to the full three-dimensional equations. The most common simplifications are averaging over one or two dimensions.
- Fate models that are part of real-time EWS models generally fall into one of three categories: representation of substances as conservative, use of a simple decay model, and development of fate parameters and processes for the most commonly encountered substances.

- A range of alternatives in terms of incorporating a model into an EWS include: development of a special purpose model, modification of an existing model, and use of an existing model without modification.
- A separate class of models were identified that modeled inland oil spills on rivers. Physical-chemical processes that affect fate and transport in these types of models include: advection due to wind and current, spreading of surface oil due to turbulent diffusion and mechanical spreading, emulsification and spreading of oil over the depth of the river, changes in mass and physical/chemical properties due to weathering, interaction of oil with the river shore lines, attachment of oil droplets to suspended particulates, photo-chemical reactions, and microbial biodegradation.

Grayman et al. (2001) summarized the state of development and applications of models as part of EWS at that point of time and highlighted the following observations:

- Most model development by 2001 had targeted planning and impact analysis applications; relatively little effort had been spent on development of models for early warning.
- Most model development had been done for very large rivers in the U.S. and Europe. Lake and reservoir modeling is more complex than riverine models.
- A critical component of source water EWS modeling is a mechanism for determining flow conditions and for predicting contaminant fate and transport. An EWS could incorporate these elements via internal tools or via link to external tools and data sources.

5.2 Taxonomy of EWS Models

Models used as part of EWSs can be categorized based on complexity, processes represented, availability of models, and model design. For the purpose of this review, the following four general categories of models have been selected:

- Physically based models: models that represent the underlying physical-chemical processes
- Geographic information system (GIS)-based models: a variety of process models that have been integrated with a geographic information system for ease in parameterizing the model and displaying results
- Data-driven models: models that rely upon analysis of large databases of observed data (input-output models) rather than emphasizing the underlying physical processes
- Simplified modeling techniques: models that have used highly simplified representations of the underlying physical-chemical processes

It should be noted that these categories are not necessarily unique and a particular model could fit into multiple categories (i.e., a physically-based model or a simplified model could be integrated within a GIS). In the following sections, progress in EWS modeling is discussed in terms of the four categories.

5.2.1 Physically based Models

Physically-based hydraulic and water quality modeling is a well-developed field that dates back over half a century. Grayman et al. (2001) provided a picture of the state of the science of physically based modeling in 2001. Wang et al. (2013) provided a review of water quality models for surface water as of 2013 while Bahadur et al. (2013) presented a state of the science review of water contamination modeling as of 2013. Advances in the field made over the past 15 years are described below.

HEC-RAS is the widely used USACE's Hydrologic Engineering Center model designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. It is currently being expanded to include riverine water quality analyses (USACE, 2016). Transport and fate of a limited set of water quality constituents is now available in HEC-RAS. The currently available water quality constituents are: dissolved nitrogen (NO_3-N, NO_2-N, NH_4-N and Org-N), dissolved phosphorus (PO_4-P and Org-P), algae, DO, carbonaceous biological oxygen demand (CBOD) and water temperature. Testing of this module and further expansion of its capabilities is currently underway. This addition to HEC-RAS is significant because of the wide use of the hydraulic model. Simultaneous hydraulic and water quality modeling allow the use of HEC-RAS within an EWS for prediction of times of travel for contaminant plumes and estimation of contaminant attenuation during transport.

The MIKE series of models (MIKE11, MIKE21, MIKE3) are three physically based models developed by the company DHI (Horsholm, Denmark) for simulating flow and water quality in one, two and three dimensions, respectively. This series of commercial modeling systems are widely used worldwide and have been implemented as part of an EWS on the Yellow River in China (Burchard-Levine et al., 2012).

Wang et al. (2013) deemed the period after 1995 as the "deepening stage" in surface water quality modeling. Advances that they identified during this period include: improvements in modeling non-point sources and inclusion of nutrients and toxic chemical materials depositing to water and land surfaces. The authors identified seven groupings of models with varying complexity and data requirements. They also noted a trend towards standardization of models and their application as evidenced by the U.S. EPA's guidance for quality assurance programs associated with models (U.S. EPA, 2002). Wang et al. (2013) called for more standardization and greater attention to validation during model development. In addition, the authors noted that models needed to be developed for the appropriate use.

Bahadur et al. (2013) conducted a state of the science review of water contamination modeling. In the paper, 65 separate models were identified and categorized in terms of environment (river, lake, estuary, coastal, watershed), degree of analysis (screening, intermediate, advanced), availability (public, proprietary, restricted support), temporal variability (steady state, time variable), spatial resolution (1-D, 2-D, 3-D), processes (flow, transport, both), water quality (chemical, biological, radionuclide, sediment), and support (user support, use manual). Based on the dates of the references given in the report, less than 25% of the models were developed or significantly updated after 2001. An examination of the post 2001 models mentioned in the review included HEC-RAS, MIKE, RiverSpill and ICWater (Incident Command Tool for Drinking Water Protection) models as the most relevant in terms of modeling as part of EWSs. These models are discussed elsewhere in the present report.

5.2.2 GIS-based Models

GIS dates back to the 1960s and 1970s (McHarg, 1969; Tomlinson, 1968). In the 1980s, Horn and Grayman (1993) introduced the concept of integrating water quality modeling into the nationwide riverine-based Reach File System for planning studies. In a demonstration project for the U.S. EPA, Grayman et al. (1994) integrated a simplified steady-state water quality model with the Reach File System using a commercial GIS package (ARC/INFO™ NETWORK [ESRI, Redlands, CA]). The system was implemented for the Ohio River Basin and could be used to calculate the path that a spill at any point in the basin would follow, and the resulting concentrations and travel time throughout the downstream path.

Since 2001, several GIS-based spill models have been proposed and implemented. A consortium of federal agencies sponsored the development of RiverSpill software, a GIS-based software package that calculates time-of-travel and concentration of contaminants in streams and rivers (Samuels et al., 2006). RiverSpill software uses real-time stream flow data, a hydrologically connected stream network (USGS Enhanced Reach File version 2.0 ERF1-2) and the locations and populations served by each public, surface drinking water intake. It could be applied to simulate deliberate contamination incidents or accidental water contamination incidents, such as spills from transportation accidents on roadways and railroad, pipelines, wastewater treatment plants and hazardous materials storage sites. ICWater (Incident Command Tool for Drinking Water Protection) software evolved from RiverSpill software and provides real-time assessments of the travel and dispersion of contaminants in streams and rivers (Samuels et al., 2015). It uses the 1:100,000 scale National Hydrography Dataset Plus, Version 1.0 (NHDPlusV1), a hydrologically connected river network that contains over three million reach segments in the United States. Mean flow and velocity have been calculated by the USGS and the U.S. EPA for each reach. These mean values are updated by flow from web accessible real-time gauging stations. ICWater software was successfully applied in near real-time during the 2014 Elk River spill incident to predict the movement of the spill in the Ohio River (Bahadur and Samuels, 2015).

Zhang et al. (2011) developed a GIS-based spill model for the Huaihe River Basin that runs through central and eastern China. The system includes database management, water quality evaluation, statistical analysis, case management, model simulation, and emergency response as features of an integrated water-pollution emergency-information-management and decision-making system for river-basin management.

Rui et al. (2015) proposed an emergency response system based on the integration of GIS technology and a hydraulic/water-quality model. Using the spatial analysis and three-dimensional visualization capabilities of GIS technology, they calculated pollutant diffusion measures, and visualized and analyzed the simulation results. The system has been demonstrated as part of an early warning and emergency response program for sudden water pollution accidents in the Xiangjiba Dam area on the Yangtze River in China.

Significant interest exists in applying GIS and modeling for oil spill response and analysis. The General NOAA Oil Modeling Environment (GNOME) has been combined with remote sensing by National Aeronautics and Space Administration (NASA) to assess the oil spill modeling potential (Spruce, 2004). Chen et al. (2010) developed a two-dimensional hydrodynamic/oil spill model based on GIS to simulate currents and oil transportation in rivers, lakes and reservoirs, and applied it to the Three Gorges Reservoir in China.

GIS-based spill models used in conjunction with national databases have the potential for significantly reducing the setup time and the effort required to implement a spill model. Unlike a conventional stand-alone spill model that requires extensive manual parameterization and calibration and thus, must be in place prior to an actual spill incident, a GIS spill model (in conjunction with an available national database) could be quickly implemented. At the extreme, such a system could be implemented after a spill is detected and used as a first-cut predictive tool to simulate the incident in near real-time. The application of ICWater model to the Elk River spill on a near real-time basis demonstrated this potential. However, establishment and testing of any spill modeling system on a river of interest prior to an actual incident will increase the confidence associated with the resulting simulations.

Though the promise of GIS as a component of EWSs is clear, numerous challenges exist in regards to its effective use in this context. First and foremost, GIS, as an information system, has significant data needs ranging from sufficiently detailed representations of stream networks, lakes and reservoirs to locations of contaminants or spill sites. The dynamics of land use, hydrology, climate and other temporally varying factors require update and maintenance of GIS data. Second, for its most effective use in an EWS, GIS should be integrated with tools such as event detection systems (inclusive of means for updating and maintaining water quality time series data) and hydraulic models. Although commercial and open source GIS packages have facilities for integrating EWS tools with GIS, integrated tools are not currently well-tested or readily available. Finally, data requirements as well as upkeep of GIS tools themselves can require dedicated staff and significant expenses.

5.2.3 Data-driven Models

Whereas physically based models are based on mathematical descriptions (i.e., the physics) of river flow and water quality transport/fate, data-driven models (DDM) rely upon various methods that analyze data sets to draw conclusions related to the nature of the problem (flow, transport and fate). Solomatine and Ostfeld (2008) described the DDM process as: "a dependence ('model') is discovered (induced), which can be used to predict the future system's outputs from the known input values" – i.e., an input-output model.

Burchard-Levine et al. (2012) identified the three most frequently used data-driven models as statistical, fuzzy logic and ANN, with ANN currently being the most widely used technique in the area of water modeling. Maier et al. (2010) reviewed 210 journal papers that were published from 1999 to 2007 and focused on the use of ANN in the prediction of water variables in river systems. Approximately 90% of the applications focused on water quantity (flow and level) with only 10% applying the method to predicting a wide range of water quality variables. The review did not explicitly indicate those studies that pertained to EWS modeling, but an examination of the reference list suggested very little research work that has been directly applied to early warning modeling.

Piotrowski et al. (2007) described a new ANN-based approach that relies heavily on measurements of concentration collected during tracer tests over a range of flow conditions to develop a predictive capability. Four separately designed neural networks were used to predict concentration versus time measurements at a particular cross-section as characterized by the peak concentration, the arrival time of the peak at the cross-section and the shapes of the rising and falling limbs.

In probably the most applicable study in the use of DDM to EWSs, Burchard-Levine et al. (2014) performed a case study in a southern industrial city in China in which a DDM based on genetic algorithms (GAs) and ANN was tested. The GA-ANN model was used to predict NH_3-N, chemical oxygen demand (COD) and TOC variables at a downstream station two hours ahead of time resulting in an increase in the response time of the city's EWS.

Deng (2014) developed a modeling capability as part of a pollution EWS for the management of water quality in oyster harvesting areas along the Louisiana Gulf Coast. The system consists of (1) an Integrated Space-Ground Sensing System gathering data for environmental factors influencing water quality, (2) an ANN model for predicting the level of fecal coliform bacteria and (3) a web-enabled, user-friendly GIS platform for issuing water pollution advisories and managing oyster harvesting water.

5.2.4 Simplified Modeling Techniques

The fourth category of models utilizes simplified relationships and methods to predict the movement of contaminants in rivers. Many of the first riverine EWSs employed such methods. Fennell (1988) described a simplified time-of-travel and peak concentration model developed by ORSANCO in response to a major oil spill in 1988. Other simplified models were applied to the Rhine River (Spreafico and van Mazijk, 1993) and the Lower Mississippi River (Waldon, 1998). Simplified models typically assume one-dimensional steady flow, calculate the relationship between velocity and flow by a simple power function equation and either ignore or use simplified methods for representing dispersion and decay. In many cases, the simplified methods utilize spreadsheets as the calculation mechanism.

Since 2001, minimal use and development has occurred in the area of simplified modeling for EWSs. The GIS-based models described earlier (RiverSpill and ICWater software) utilize modeling methods that could be best described as enhanced simplified modeling that fall between simplified models and physically based models.

6.0 EWS Data Integration and Communication

Previous chapters in this report have presented information on specific components of EWSs including monitors, modeling and event detection. However, in order for there to be a 'system' in EWSs, linkages between the individual components are needed. U.S. EPA developed guidance on designing a real-time source water quality monitoring system to detect source water contamination incidents that provides information on data integration and communication (U.S. EPA, 2016c). In this chapter, three forms of linkages are discussed and past work in these areas are reviewed: data integration, communications and institutions.

6.1 Data Integration

EWS data can include:

- Water quality data (data input to and managed by an EWS)
- Other data that could indicate a water quality incident of significance to drinking water operations and their customers (e.g., spill reports, CSOs, incident notifications)
- Contextual data such as spill locations, drinking water treatment operation intake locations, zones of critical concern, watershed boundaries, locations of potential contaminants of concern (e.g., storage tank locations)
- Interpretive data such as alarms and event detection application outputs and inputs
- Incident response data such as actions taken in response to an incident (including classification of an anomalous water quality change as a non-incident), results from sampling in response to an incident

Although an EWS does not necessarily house and use all of those data, access to all of them could facilitate improved incident detection and response.

The data described above are likely to come from a variety of agencies (e.g., U.S. EPA, state regulatory agencies, public water system monitoring data, USGS) and differ in their structure, completeness and use. Ideally, an EWS would have the ability to integrate those data in a tool that enables their effective use and maintenance. Such a tool would give users a unified view of the data and means for easily querying other pertinent data.

Three software tools have been developed for data integration as related to source water protection, spill response and incident detection. Each of these systems utilizes a GIS platform to display spatial data and integrates information derived from public databases and other data sources. The three tools are described below.

- The Drinking Water Mapping Application for Protecting Source Waters (DWMAPS) application is an internet-based GIS tool for drinking water source water protection and assessment (U.S. EPA, 2016a). The DWMAPS tool is currently under active development for the U.S. EPA's Office of Ground Water and Drinking Water. It includes a mapping tool, a linked source water protection planning tool and a suite of data exchange services that could be used to display and assess contextual data and identify potential contamination sources.
- The ICWater tool is a GIS-based tool developed for a consortium of federal agencies (see the section on GIS-based models in chapter 5 for additional information on this system).

The ICWater tool is linked to national databases containing information on dams, reservoirs, water supplies, gauges, municipal and industrial dischargers, and transportation networks. It integrates a riverine contamination model and the aforementioned national databases, within a near real-time response framework.

- WaterSuite® software (Rockland, MA) is a suite of tools integrated into a GIS framework (Rosen and Kearns, 2015). Tools currently in place within WaterSuite software are a source water assessment and protection tool, a water quality data management and event detection tool, a distribution system data management and analysis tool and a drinking water treatment database. Source water protection data housed in WaterSuite software include federal, state and local data sets with features related to potential sources of contamination, a contaminants database and data created and managed by utilities using the tool. At present, the water quality data management and event detection module pulls georeferenced, time-stamped online water quality data from sensors, houses those data in an efficient data structure and displays those data in a user interface. Near-future developments of the water quality module include integration of event detection software.

In a related area, the (U.S.) Federal Geographic Data Committee and the Advisory Committee on Water Information launched the Open Water Data Initiative in the summer of 2014 (Rea et al., 2015). The goal of the initiative is to bring currently fragmented water information into a connected, national water data framework by leveraging existing systems, infrastructure and tools to underpin innovation, modeling, data sharing and solution development. As part of this effort, a workgroup consisting of representatives from the U.S. EPA, U.S. Department of Homeland Security (DHS), USGS, NOAA, private industry and academia has been formed to investigate existing applications that address modeling and simulation, web services, GIS mapping, hydrology, emergency response, exercises and contingency planning.

6.2 Communications

Communications is a significant aspect of EWSs that includes (1) communication between sensors and a central control point, (2) communication between the central control point and a user interface or other data visualization and analysis tool, (3) communication between agencies and (4) communication between agencies and the public. Ideally, communication between agencies and agencies and the public is two-way and is conducted through the most appropriate channels for each stakeholder group. Communication of EWS data is done in the context of overall incident response communication and coordination. The communication could include the involvement of multiple cities, states, or other structures like incident command operations external to the EWS. Effective communication of EWS technical information could pose greater challenges than collection and analysis of the technical information and can be a focus for future EWS research and development. U.S. EPA provides guidance and tools on the topics of communications technologies, information management, consequence management, and risk communication for water quality surveillance and response systems that could be useful for source water EWSs at https://www.epa.gov/waterqualitysurveillance/water-quality-surveillance-and-response-systems-guidance-and-tools.

Panguluri et al. (2005) described the options for communication between field-based sensors and a central control point. The authors listed the factors influencing the selection of communication technologies as availability, cost, user preference, and the relative location of the sensors to the data acquisition system. Additional factors the authors have encountered when establishing communication between field-based sensors and a central control point include accessibility (including strength of cellular signal, if that mode is selected, and access to a power supply) and security concerns (e.g., isolating communications from critical network infrastructure).

Communication can be conducted either by wired (e.g., direct, phone line) or wireless (e.g., radio, cellular, satellite, WiFi®, ZigBee®, Bluetooth®). Campisano et al. (2013) described real-time control of urban wastewater systems and details on the communication options that are available for collecting water quality data and controlling the wastewater collection system. Communication options include phone lines (leased or dial-up), ethernet networks over fiber optic or copper cables (private or leased networks), cellular data communication services and radio communication networks (licensed or unlicensed). Radio communication can be effective for communication over relatively short distances and has been demonstrated during prior water quality monitoring studies (e.g., Anvari et al., 2009; Dehua et al., 2012; Glasgow et al., 2004; Jiang et al., 2009). U.S. EPA provided guidance on designing communication networks for water quality monitoring systems (U.S. EPA, 2016b).

The National Response Center (NRC) is the federal government's national communications center, which is staffed 24 hours a day by USCG officers and marine science technicians. The NRC is the sole federal point of contact for reporting all hazardous substances releases and oil spills. The NRC receives all reports of releases involving hazardous substances and oil that trigger federal notification requirements under several laws. Reports to the NRC activate the National Contingency Plan and the federal government's response capabilities. It is the responsibility of the NRC staff to notify the pre-designated on-scene coordinator assigned to the area of the incident and to collect available information on the size and nature of the release, the facility or vessel involved and the party(ies) responsible for the release. The NRC maintains reports of all releases and spills in a national database.

For specific localities and types of spills, a variety of mechanisms have been developed to help communicate and manage spills. Two examples include:

- The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) coordinates with the City of Chicago and all suburban municipalities to notify suppliers of potable water of contamination from CSOs. MWRDGC has created a web page (http://www.mwrd.org/irj/portal/anonymous/overview) on their website to inform the general public of the occurrences of CSOs. A color-coded graphic representation of the waterways appears on the web page depicting the occurrence of CSOs and waterway diversions to Lake Michigan.
- The Metropolitan Sewer District of Greater Cincinnati and its partners, Sanitation District No. 1 of Northern Kentucky (SD1) and ORSANCO have developed the Recr8OhioRiver website and an associated software application. It provides Ohio River water quality information and river conditions in the Greater Cincinnati area to recreational users and others as they are planning to boat, fish, swim, or engage in other water sports (http://www.recr8ohioriver.org/default.aspx) (accessed January 19, 2016).

6.3 Institutions

Based on the case studies documented in this report, a variety of institutional structures are available for managing spills. These include public regional agencies, industry groups and utility managed systems (individual utilities or consortiums).

Grayman et al. (2014) discussed institutional issues as follows:

- Multiple agencies and institutions might be involved in the detection, co-ordination and mitigation of a spill incident. Since rapid response is generally important in dealing with a spill, pre-planned institutional responsibilities, protocols and arrangements are needed.
- Effective spill response requires a lead organization to serve as the overall coordinator during emergency incidents. The lead agency can be a regional agency, a governmental unit or a water utility. Examples of such organizations include international agencies (Rhine River), state agencies (Louisiana), federal-state commissions (ORSANCO, Ohio River), water utilities (UK), a group of water agencies (Japan) and private organizations (St. Clair River).
- Other agencies that could be involved in spill situations in the U.S. include the NRC, the USCG, state and federal environmental agencies, USACE, local health and environmental agencies, emergency responders, law enforcement organizations and water utilities. Effective interaction among the agencies is a key to successful operation during a spill situation.

7.0 Conclusions and Research Needs

Based upon the state-of-the-science review of research on EWSs, several conclusions and needs have been identified relative to the research, development and establishment of source water EWSs.

7.1 Conclusions

Interest in EWSs for addressing and responding to contamination incidents in surface water systems has recently increased as a result of several high profile incidents. Contamination incidents might be caused by a wide range of sources including industrial and transportation related spills, non-point sources and urban runoff, intentional contamination, and natural processes. EWSs encompass much more than just monitors; rather they include mechanisms for detecting, characterizing, communicating and responding to contamination incidents in order to reduce and mitigate the impacts. Lak Though commonalities exist between source water EWS and contamination warning systems in drinking water distribution systems, there are significant differences in terms of the sources of contamination, the configurations of the receiving water infrastructure (pipes versus rivers/lakes), the characteristics of the water medium (raw versus finished water), the response protocols, and the methods of selecting and siting monitors to detect the presence of contaminants.

Following the terrorist incidents on September 11, 2001, emphasis in the area of EWSs shifted to potential intentional contamination of water distribution systems resulting in a robust research, development and implementation program for contaminant warning systems in drinking water distribution systems. In the last quarter of the twentieth century, a significant number of EWSs for source waters were established around the world, in most cases, in direct response to contamination incidents. A chemical spill into the Elk River in West Virginia in 2014 followed by several other much publicized spills has reinvigorated the interest in source water contamination EWSs. In addition, the threat of HABs in drinking water source water has emerged in recent years as a significant challenge to the drinking water community. Early warning activities focused on detecting HABs differ significantly from most water quality contaminants and additional research is needed in this area.

New online water quality monitoring technologies are emerging for use in EWSs. Online technologies automatically collect and communicate data and monitor a flowing sample or collect and analyze discrete samples. Emerging technologies vary widely in their state of development (from conceptual to commercialized), the focus on contaminants of relevance to drinking source water, and the potential for field deployment. The most relevant emerging technologies to drinking source water EWSs are biomonitors (monitors using the response of biological organisms to water constituents) and spectroscopic instruments (instruments sensing absorbance, transmittance and scattering/reflectance of electromagnetic radiation).

Several criteria should be used in selecting monitoring technology for use in an EWS: cost, spectrum (broad spectrum or specific constituent), sensitivity, operational and maintenance requirements, environmental requirements (power, shelter), sampling frequency, and communications requirements. Though many studies have addressed the design and siting of monitors within distribution systems, only limited research has been done into siting monitors in source waters. In actual practice, monitors are generally placed in a more ad hoc manner based on “covering” stretches of rivers that are most susceptible to spill incidents, in the vicinity of important water intakes and locations where the monitors can be easily serviced and managed.

Similarly, many event detection methodologies and techniques have been applied successfully to drinking water distribution systems, but their application to source water event detection has been limited. Source water quality is much more variable than water quality in distribution systems, making anomalous water quality incidents more difficult to discern from background variations. Additionally, rainfall and runoff are regular occurrences for source water and it is unclear how event detection methodologies will account for water quality changes associated with these common occurrences that sometimes would not be considered contamination incidents. Some initial application studies are promising, but additional work is needed to determine the applicability of existing technologies to surface water EWS. If techniques developed for drinking water distribution system event detection do not perform as well for source water incident detection, it is possible that techniques such as artificial neural networks, correlations between multiple water quality parameters, or development libraries of user-defined signatures of non-incidents could be used to modify existing algorithms for better application to source water incident detection.

Spill models are a class of models that are used to trace the movement and fate of transient contaminants in receiving waters. They can be used in an EWS in real-time or near real-time situations to assist in the response to a spill or other transient contaminant incidents or could be used in historical reconstruction of past incidents. Models have been categorized as physically based models, GIS-based models, data-driven models and simplified modeling techniques. Prior to 2000, most models were physically based models, simplified models or rudimentary GIS-based models. Since 2000, development and research in spill modeling has emphasized data-driven models and GIS-based models. Data-driven models utilize artificial neural networks, fuzzy logic, statistical methods and other methods to model flow and water quality in rivers. GIS-based models integrate models with GIS and national databases, such as the USGS National Hydrography Dataset, and facilitate EWS modeling with minimal setup and parameterization.

EWSs are composed of the individual components of monitoring, modeling and incident detection. However, in order for an EWS to function effectively, linkages should exist between the individual components. These linkages include data integration, communications and institutions. A single platform to integrate data from the individual components can make an EWS more efficient.

7.2 Research Needs

To better understand the performance, detection capabilities and limitations of source water EWSs, more research needs to be conducted. One important aspect of identifying research needs is to conduct more assessments on existing EWSs. The assessments could provide data on the type of contamination incidents that are routinely detected and the types of contamination incidents that are not detected by EWS. More information on the effectiveness of an EWS could be completed by conducting a simulation study to assess the likelihood of detecting a broad set of potential contamination incidents given different types of EWS. Additional future research needs identified as part of this study are in the areas of contaminant information, monitoring technologies, placement of monitors, event detection methodologies, fate and transport models and data management and visualization tools.

7.2.1 Contaminant Information

To improve the effectiveness of a source water EWS, more information is needed on the contaminants that might be a possible threat. The research needs associated with this involved:

- Developing tools that enable better access to contaminant information in the watershed, such as inventories of shipping cargo for rail cars, barges and trucks, storage tanks near surface water, and pipelines crossing surface water bodes
- Evaluating the need for this information to be available in real-time, spatially and temporally, in order to be linked to surface water modeling and simulation tools

Determining kinetic, partitioning information, and reaction dynamics for the contaminants that are of greatest concern

7.2.2 Monitoring Technologies

In terms of the monitoring technologies used for source water early warning systems, research needs identified in the development of this report include:

- Determining which parameters to monitor and how they relate to the contaminants of greatest concern to a drinking water utility or downstream use
- Assessing the data available from existing EWS to better understand the field performance of various monitoring technologies
- Evaluating monitoring technologies through bench, pilot and field scale testing for emerging contaminants and harmful algal blooms, such as:
    - Biomonitors
    - Spectroscopic instruments
    - Fluorescence/spectral instruments
    - Hydrocarbon detection instruments
    - Multi-parameter probes
    - Optical monitors (e.g., DO)
    - Detailed organic matter monitors (related to DBP formations)
    - Solid state and lab-on-a-chip technologies
- Developing monitoring technologies that are:
    - More reliable real-time instruments to operate in source water with varying water quality
    - More practical and accurate for inorganic contaminants

7.2.3 Placement of Monitors

More research needs to be completed to help identify where monitors should be located with the source water to be the most effective for the purposes of the early warning system. This could involve the following activities:

- Developing approaches and tools that incorporate upstream threat analysis to go beyond the traditional approach of siting monitors near an intake or just downstream of a known threat. Upstream threat analysis and identification of monitoring locations should consider the area tens to hundreds of miles upstream of a drinking water intake to account for variations in flow rates, volumes, speeds and contaminant characteristics (e.g., conservative, volatility, density), since time-of-travel can vary from days to weeks with different downstream peak concentrations.

- Evaluating the siting of monitoring locations as part of resilience planning. Monitoring locations could be selected in such a way as to improve the utility's ability to react and respond to spills and to plan for long-term capital improvements (asset management). Resilience planning can include both long term chronic risks (lower concentration) and acute spills (higher concentrations) to evaluate the utility's ability to counter different threats by:
  - Intake closure/finished water storage
  - Treatment (emergency or permanent change to the treatment train)
  - Alternative sources of raw/finished water
- Evaluating the placement of monitoring locations in regards to how they might be used to enhance daily operational controls for large reservoirs on tributaries and on navigational locks and dams. Water quality/volume can be accounted for in multiple-use reservoir flow releases for flood and water quality management, and how they impact downstream water quality and navigational needs.
- Evaluating the siting of monitoring locations based upon a contamination scenario, in which multiple individual worst case scenario emergency response plans are combined. An example scenario could be a chemical tank that ruptures and spills into the river, and then, during the response, a barge carrying a different chemical compound wrecks and spills its content into the river as well.

7.2.4 Event Detection Methodologies

Additional research needs are associated with the application of EDS to source water applications. These needs could include:

- Assessing the data available from existing EWS to better understand current false positive detection rates and what causes them
- Evaluating the existing EDS tools and approaches on water from a variety of surface water bodies to develop correlations between multiple water quality parameters and contaminants of concern
- Developing libraries of events/alarms associated with common contaminants and user-defined signatures of non-incidents to help reduce the high frequency of false positive assessments
- Developing additional EDS techniques that could explore the use of artificial neural networks

7.2.5 Fate and Transport Models

Another research area identified in this study is related to fate and transport models that could be used to support source water early warning systems, including:

- Developing approaches to link real-time data (e.g., flows, levels, water quality parameters) with surface water modeling and simulation tools to obtain a more accurate representation of the water system
- Developing modeling and simulation tools that incorporate the whole watershed, such as overland flows, surface water flows, wastewater discharges, and drinking water distribution systems
- Developing linkages between the fate and transport models and GIS databases which contain information about the type of contaminants that might be in the watershed

- Incorporating cross-sectional stream geometries, if available, into three-dimensional surface water models to support more accurate fate and transport of spills
- Evaluating the need to verify and calibrate three-dimensional models to determine if the accuracy is necessary to support effective source water early warning systems

7.2.6 Data Management and Visualization Tools

In addition, a source water EWS requires data management and visualization tools to support analytics and communication. Some research needs identified in the study include:

- Developing better data transmission tools to support monitor at remote sensing locations
- Evaluating alternative power supply options to remote sensing locations
- Developing enhanced data analysis and visualization tools to support real-time response actions
- Developing a reliable method for validating data from online instruments in real-time
- Evaluating vulnerabilities in the data communication pathway, including cybersecurity concerns
- Evaluating the benefits of sharing data with a wider set of stakeholders
- Evaluating techniques to incorporate reporting of contamination incidents from social media, citizen science, or other public sources

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Appendix A – Detailed Case Studies

Appendix A Table of Contents

A 1. Danube and Tisza River Basin Case Study

Location	Danube and Tisza River Basin
Source Water	Danube and Tisza River Watershed
Coordinating Agency	International Commission for the Protection of the Danube River (ICPDR)
Start Date	1997

System Description

The Danube River runs 1,775 miles (2,857 km) from Germany to the Black Sea. The Danube River Basin includes the watersheds of multiple tributaries, the largest of which is the Tisza River (Appendix Figure 1). Home to over 81 million people, the region spans 309,447 square miles (801,463 square kilometers) in Albania, Austria, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Italy, Macedonia, Moldova, Montenegro, Poland, Romania, Serbia, Slovakia, Slovenia, Switzerland and Ukraine (ICPDR, 2011).

Appendix Figure 1. Danube and Tisza River Basins (WWF, 2002).

The Tisza River runs 600 miles (966 km) from Ukraine to Serbia, where it meets the Danube River. The Tisza River Basin is home to approximately 14 million people and spans 60,690 square miles (157,186 square kilometers) in Romania, Hungary, Slovakia, Ukraine and Serbia

(VRIC & EI, 2014). The Danube River and its tributaries are valuable resources for drinking water, transportation, agriculture, industry and recreation.

The Danube Accident Emergency Warning System (DAEWS) was implemented in 1997 in Austria, Bulgaria, Czech Republic, Croatia, Germany, Hungary, Romania, Slovakia and Slovenia. In 1999, the system was extended to Ukraine and Moldova and in 2005 the expansion grew to include Bosnia-Herzegovina and Serbia (ICPDR, 2016). System operation, maintenance and upgrades have been managed by the International Commission for the Protection of the Danube River (ICPDR) Secretariat (ICPDR, 2015a). In each of the member countries, a Principal International Alert Center (PIAC) ("Alert Center") was established to manage communications. The DAEWS is operated as a partnership and communications network between the Alert Centers, with overall management from the ICPDR. The Alert Center in each country relies on the national AEWS, which is separate from the DAEWS and managed solely on a national level (ICPDR, 2014).

"Appropriate control of accidental pollution is essential in order to mitigate adverse effects of hazardous substances spills…The Accident Emergency Warning System (AEWS) was developed to…recognize emergency situations. It is activated if a risk of transboundary water pollution exists and alerts downstream countries with warning messages in order to help national authorities to put safety measures…into action." (ICPDR, 2015a).

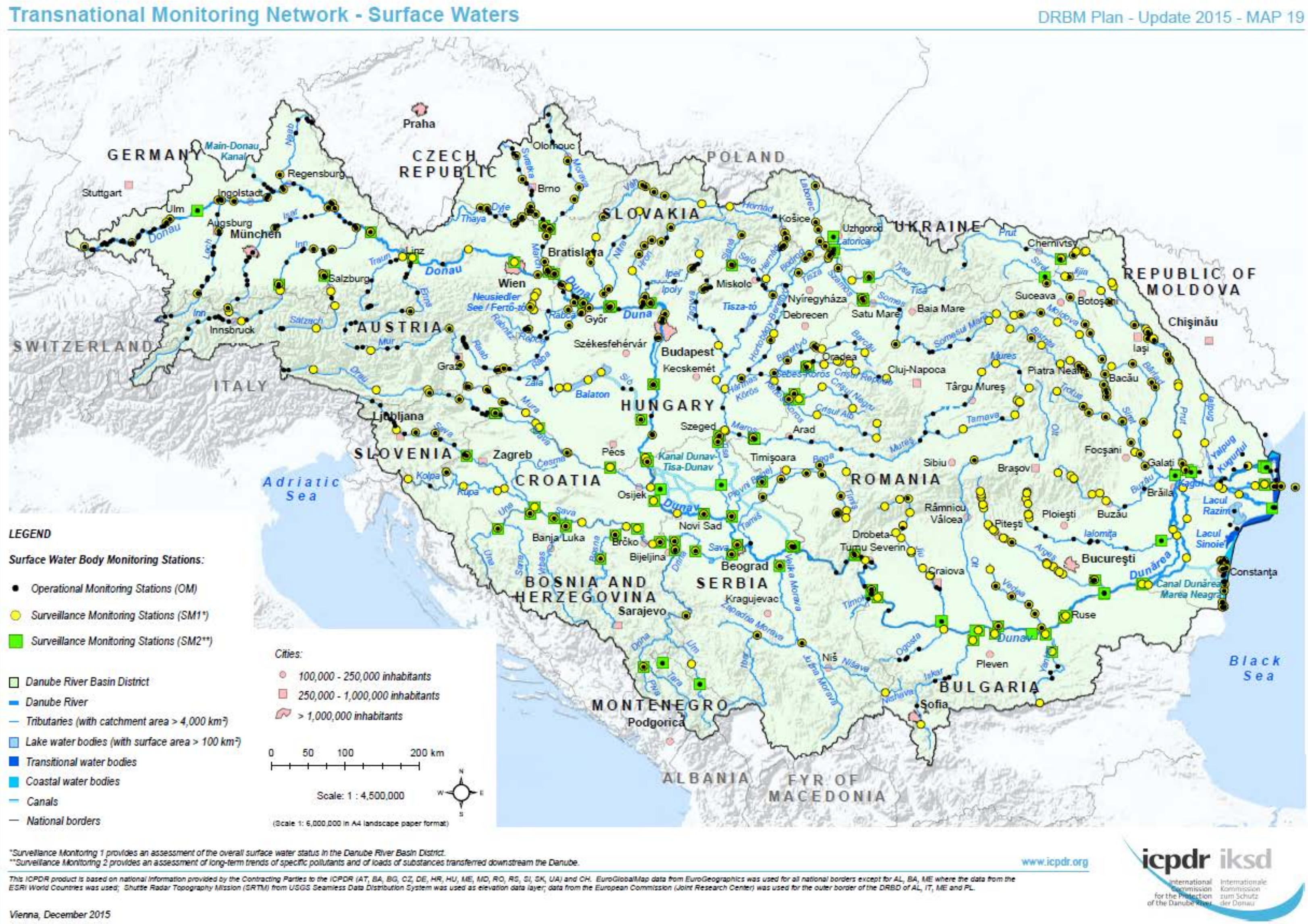
In addition to the DAEWS, an early warning system (EWS) is being considered for the Tisza River Basin. A study was conducted by the Veszprémi Regionális Innovációs Centrum Nonprofit Kft. and Environmental Institute to (VRIC & EI, 2014):

- Consider monitoring locations and constituents of interest
- Assess monitoring equipment options
- Examine existing EWS applications
- Develop anticipated capital and operational costs

The existing DAEWS consists of: (1) a partnership of stakeholders, (2) a periodic water quality monitoring network, (3) an international communication and alert system and (4) a web and database portal. The proposed Tisza River EWS would include continuous water quality monitoring with real-time data transmission (VRIC & EI, 2014).

Monitoring Network

The water quality monitoring component of the DAEWS is referred to as the TransNational Monitoring Network (TNMN), a network of water quality monitoring programs in member countries. Illustrated in the Appendix Figure 2, the TNMN includes 79 monitoring stations and measures 52 water quality parameters at least 12 times per year (ICPDR, 2016; VRIC & EI, 2014). In addition to the periodic monitoring of the TNMN, the DAEWS relies on water quality monitoring and incident notification through the national Accident Emergency Warning System (AEWS) of each country with Alert Centers as the central points of the communication network.



Appendix Figure 2. Danube River transnational monitoring network (ICPDR, 2015b).

Data Management and Communication

The DAEWS includes a website with tracking of incident reports and alerts and a database of chemical information.

Communication and Response Network

The basis of the communication and response network are the Alert Centers. The DAEWS is triggered when an Alert Center is notified of a pollution incident through the national AEWS. The primary tasks of the Alert Centers are communication, assessment and decision-making. Incidents are reported via the DAEWS website with email and text notifications to affected parties, including downstream Alert Centers. The notification network is operational 24-hours/day, with telephone backup.

Future Development

As of the 2014 report, the proposed addition of an EWS for the Tisza River would proceed as follows (VRIC & EI, 2014):

- Feasibility study in 2014
- Pilot project in 2014 through 2015
- EWS basic basin-wide development in 2016 through 2018
- EWS expansion and additions in 2019

Challenges, Insights and Operational Notes

The DAEWS enables communication across national boundaries between many countries of varying governing structures, priorities, cultures and economies. Essential aspects include agreement between countries within the Danube River Basin and standardization of operations, reporting and communication. The Alert Centers are the core component of the system, functioning as the connection between national authorities and international communications.

Contact Information

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A 2. Delaware Valley Case Study

Location	Delaware Valley
Source Water	Delaware and Schuylkill River Watersheds
Coordinating Agency	Philadelphia Water Dept., EWS Steering Committee, Advisory Committee
Start Date	2004

System Description

The Delaware River runs 330 miles from Hancock, New York to the Delaware Bay. The Delaware River Basin is comprised of the Schuylkill River and Delaware River watersheds (Appendix Figure 3). Home to approximately 8 million residents, the region spans 13,500 square miles in parts of Pennsylvania, New Jersey, New York and Delaware (DRBC, 2013). The two rivers and their tributaries are not only valuable resources as drinking water supplies, but also for transportation, agriculture, industry and recreation.

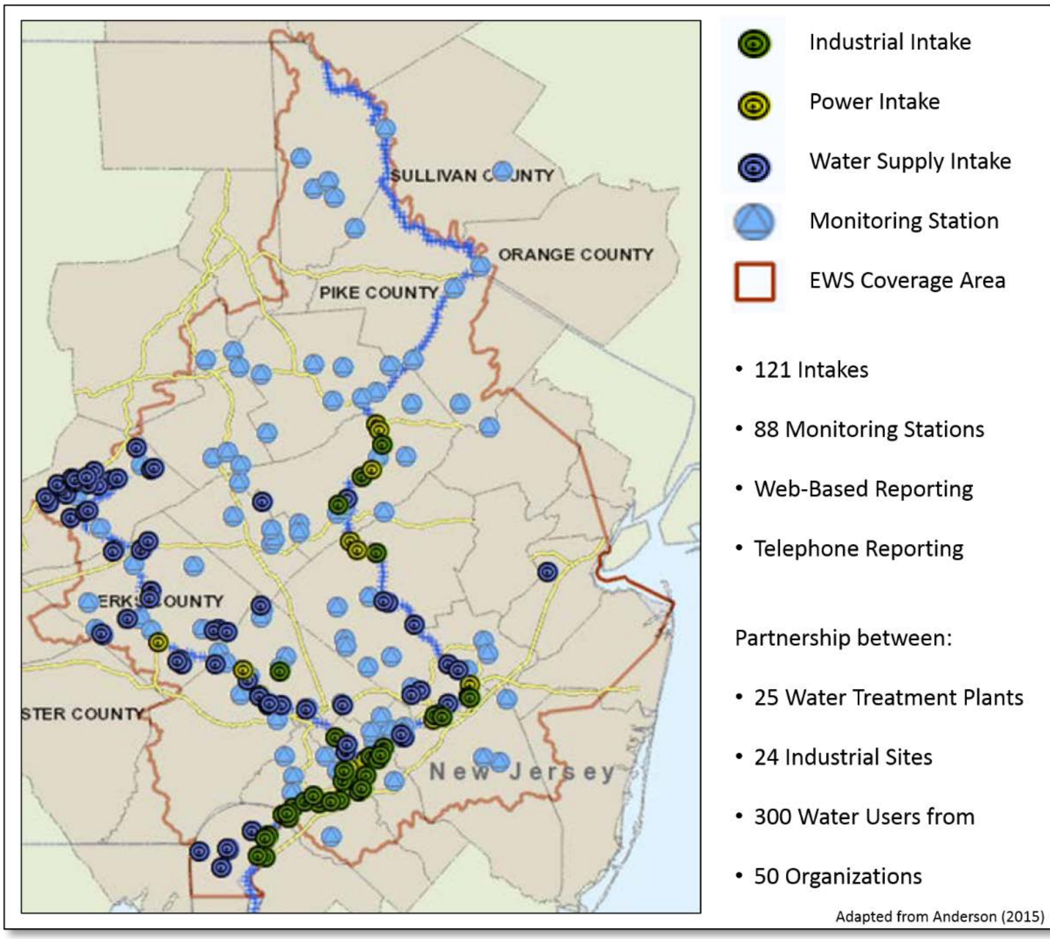
Appendix Figure 3. Delaware Valley water basin (Anderson, 2015).

"The EWS provides advanced warning of water quality events, web-based tools for determining proper event response, and a strong partnership between water users and emergency responders in the Schuylkill and Delaware River watersheds" (Philadelphia Water Department, 2008).

As part of the region's Source Water Protection Program, the Philadelphia Water Department led the development of the Delaware Valley Early Warning System to enable advanced notification to water users of contamination incidents and changes in water quality. Implemented in 2004, the system was developed and is operated as a partnership between 300 water users in 50 organizations. Members include 25 water treatment plants (21 plants from 13 utilities in Pennsylvania and four plants from four utilities in New Jersey), 24 industrial sites (in Pennsylvania, New Jersey and Delaware), the Pennsylvania Department of Environmental Protection (PA DEP), the New Jersey Department of Environmental Protection (NJ DEP), the Delaware River Basin Commission (DRBC), U.S. EPA, U.S. Geological Survey (USGS), U.S. Coast Guard (USCG), county offices of emergency management and county health departments (Anderson, 2015). The governing body of the system is the EWS steering committee, which is comprised of utility representatives. Government agency representatives participate through an advisory committee. The funding structure for the system is based on a user fee from drinking water utility and industry members. Highlighting the success of the system, the Delaware Valley EWS received the 2015 Pennsylvania Governor's Award for Environmental Excellence (Philadelphia Water Department, 2015). The Delaware Valley EWS consists of four key elements: (1) a partnership of stakeholders, (2) a monitoring network, (3) a notification system and (4) a web and database portal.

Monitoring Network

The system includes two monitoring pathways: (1) telephone and web-based incident reporting and (2) water quality monitoring stations throughout the watershed. Contamination incidents are reported by emergency personnel, water system representatives, or other EWS members through a web-based form or via telephone. The incident time, location, and additional details are recorded, which triggers automatic notification procedures. Water quality data are collected every 15 minutes from 88 locations (Appendix Figure 4) including drinking water treatment plant intake locations and USGS monitoring stations, with remote data transmission to the system's server (Duzinski, 2008). At drinking water treatment plant intake locations, real-time monitoring equipment measures dissolved oxygen (DO), turbidity, temperature and conductivity (Duzinski, 2008). The current EWS coverage area includes 121 intakes, 280 miles of river, 7,400 miles of stream and 88 water quality monitoring stations (Anderson, 2015).



Appendix Figure 4. Delaware Valley monitoring stations (adapted from Anderson, 2015).

Data Management and Interpretation

The Delaware Valley EWS database manages both reported incident data and water quality monitoring data. The database is accessible through a secure web portal. Water quality data are available for every 15 minutes of the preceding 30-day period and as a daily average dating back several years. Additional water quality information, collected through standard water treatment plant operations, is logged as well. The portal includes online tools to access water quality and incident data and to view and analyze water quality data. Historical USGS flow data are incorporated into the time-of-travel model to predict arrival times at downstream locations (Gullick et al., 2004). In addition to incident assessment and water quality data analysis, the web portal enables spill model analysis and integrated mapping. Most recently, the EWS has developed a tidal model to assess the impact of tidal flow in the Lower Delaware River.

Communication and Response Network

The system is fully automated such that incident reporting triggers the time of travel model and automatically notifies system users, without the need for 24-hour staffing. Timely notification of incidents is facilitated by consistent formatting of incident reporting. The automated incident reporting and notification system has the ability to quickly provide warning to a large area, allowing for expedited response.

Future Development

The Delaware Valley EWS was designed as a framework capable of expansion and perpetual enhancement. Since the system became operational in 2004, numerous improvements have been made and upgrades and advancements are ongoing. Anderson (2015) identified the future plans as:

- Monitoring for additional parameters
- Increasing monitoring locations
- Technology upgrades
- Expansion of user base and geographical coverage
- Enhancement of web-based geospatial and modeling tools

Challenges, Insights and Operational Notes

An essential element of the system's success is the partnership approach encouraging active user participation. With member participation in the EWS steering committee, member priorities can be addressed with the appropriate guidance of the advisory committee.

The automated incident reporting and notification system allows for prompt and wide-reaching dissemination of time-sensitive information, without the need for 24-hour staffing.

Regional water consumer participation and interest in the Delaware Valley EWS has been promoted by the potential adaptability of the developed network for other applications (e.g., Department of Health interest in application of the network as a recreational waterborne disease tracking tool) (Gullick et al., 2004).

Contact Information

Philadelphia Water Department, Source Water Protection Program Manager, Kelly Anderson, (215) 685-6245, kelly.anderson@phila.gov.

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A 3. Great Lakes Case Study

Location	**Lake Erie**
Source Water	Lake Erie
Coordinating Agency	NOAA Great Lakes Environmental Research Laboratory (GLERL)
Start Date	1989 (Starting date for the Cooperative Institute for Limnology and Ecosystems Research)

System Description

The Great Lakes Harmful Algal Blooms (HABs) Program is a collaborative effort between scientists at National Oceanic and Atmospheric Administration (NOAA), Great Lakes Environmental Research Laboratory (GLERL) and the Cooperative Institute for Limnology and Ecosystems Research (CILER). Project goals are to provide a five-day prediction of the severity and movement of HABs on Lake Erie. Elements of the effort are water quality monitoring, including near real-time microcystin concentration monitoring, collection and analysis of satellite and hyperspectral data, modeling and forecasting and communication of results to the general public via web tools and a periodic Lake Erie HAB bulletin.

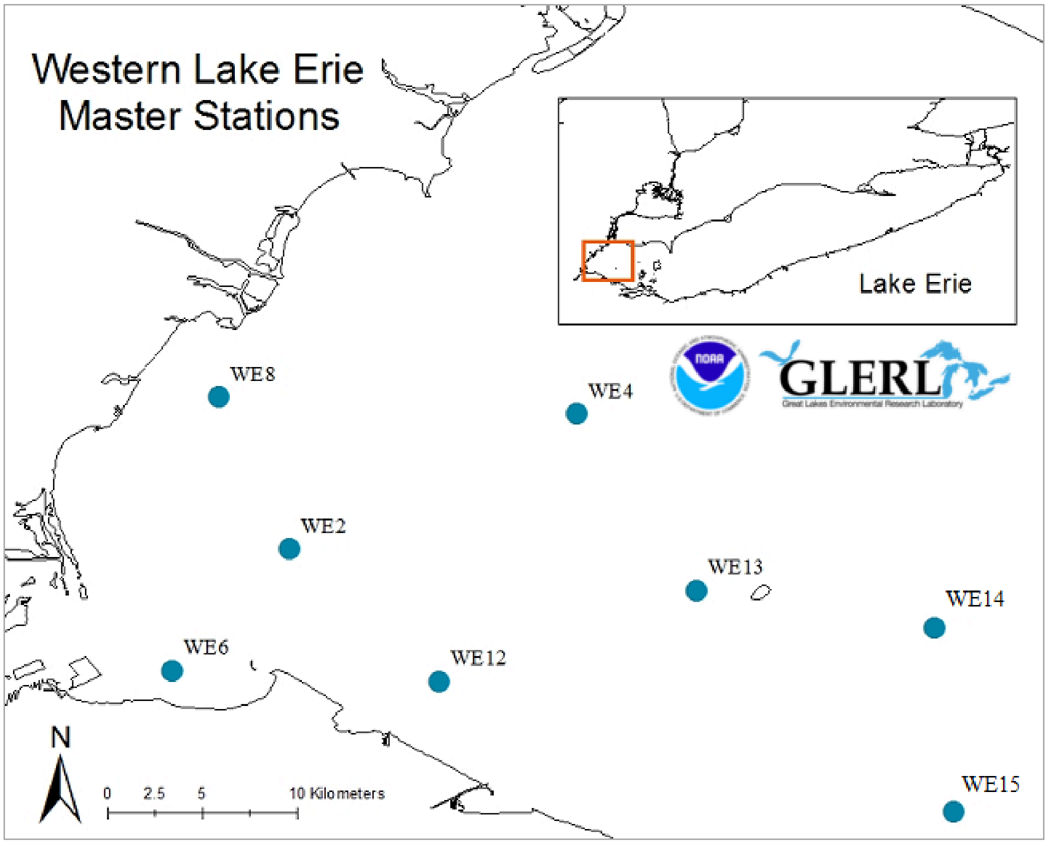
Monitoring Network

Satellite data, in conjunction with remote sensing buoys, and a comprehensive physical monitoring program are used to forecast HABs. From 2002 through 2011, medium-spectral resolution imaging spectrometer's (MERIS's) satellite data was use to model cyanobacterial blooms (Stumpf et al., 2012). Starting in 2012, MERIS lost communication and could no longer be used, so Moderate Resolution Imaging Spectrometer's (MODIS's) satellite data has been used since that time. The physical sampling locations are mapped in Appendix Figure 5. Four remote sensing buoys collect the following data every 15 minutes (NOAA GLERL, 2016):

- Air temperature
- Water temperature
- Barometric pressure
- Wind speed
- Wind direction
- Turbidity
- Conductivity
- Phosphorus
- Chlorophyll-a
- Blue-green phycocyanin
- Fluorescent decomposed organic matter

The following data are collected at the surface, 0.75 meters below the surface and 1 meter above the bottom of the lake:

- Particulate microcystin
- Dissolved microcystin
- Chlorophyll-a
- Phycocyanin
- Temperature



Appendix Figure 5. Western Lake Erie sample locations.

Data Management and Interpretation

Unprocessed satellite data is gathered from the NASA MODIS – Terra and aqua satellites, and is then modeled into cyanobacteria biovolume using the second derivative spectral shape algorithm (Wynne et al., 2008). This algorithim uses a change in the shape of the spectral curve at 681 nm to distinguish cyanobacterial blooms from algal growth. The fly over time for the MODIS satellites is every one to two days. Real-time monitoring data is collected from the solar-powered bouys and transmitted by a cellular network. Weekly physical samples are collected by University of Michigan in conjuction with NOAA GLERL.

Communication and Response Network

A forecast bulletin is issued up to every two days during the bloom season to subscribers and is available online to the general public. The online HAB tracker is updated daily with a five-day forecast. All of the real-time, field measurements, laboratory data and bulletins are publically available online, along with the satellite images.

Future Development

Satellite images are limited to a water depth of 1 meter. Wind can push cyanobacterial cells lower in the water column, which causes inaccuracy in forecasting (Wynne et al., 2010). A three-dimensional model is being developed that will account for the impact of the wind. The model will be in experimental trials during 2016 (personal communication Timothy Davis, NOAA GLERL, January 27, 2016). This model will help drinking water managers to determine at what depth to expect cyanobacteria and will also help managers to improve the forecasting capabilities of HAB tracker.

An experimental model will be developed based on data from the environmental sample processer on the buoys, with a goal of forecasting the toxicity of the bloom.

The Cyanobacteria Assessment Network (CyAN) is a collaboration between NOAA, USGS and U.S. EPA (U.S. EPA, 2016). Remote sensing data will be produced by the Sentinel-2, Sentinel-3, and Landsat satellites (Schaeffer et al., 2015). Data collected from Sentinel-3 is of particular interest because it is equipped with a sensor that is expected to have better sensitivity and resolution than the MODIS or MERIS sensors (Lunetta et al., 2015). The sensor on the Sentinel-3 is called the Ocean Land Colour Instrument (OLCI). Sentinel-3 was launched in February of 2016, and has begun producing data. Data from Sentinel-3, processed through the model that has been developed for remote sensing in Lake Erie, will be used in Ohio, California, Florida, New Hampshire, Massachusetts, Connecticut and Rhode Island.

Challenges, Insights and Operational Notes

The estimated threshold for cyanobacteria detection is 20,000 cells/mL (NOAA Great Lakes Environmental Research Laboratory, 2015b). This is the same value as the WHO guideline level for recreational waters, which is based on the skin irritation impacts, and not the toxicity of microcystin that is ingested (WHO, 2003). A count of 20,000 cells/mL is in the high alert level range for drinking water sources (Newcombe et al., 2010). The alert levels are summarized in Appendix Table 1. Drinking water alert levels are lower than the recreational alert levels because they account for the toxicity of ingested microcystin. For drinking water forecast and early warning, it would be ideal to have a lower detection threshold.

Appendix Table 1. Drinking Water Cyanobacteria Alert Levels (adapted from Newcombe et al., 2010)

Alert level	Cell count
Low alert	500 to 1,999 cells/mL of cyanobacteria
Medium alert	2,000 to 6,499 cells/mL of *Microcystis aeruginosa*
High alert	6,500 to 64,999 cells/mL of *Microcystis aeruginosa*
Very high alert	More than 65,000 cells/mL of *Microcystis aeruginosa*

Newcombe et al., 2010. Management Strategies for Cyanobacteria (blue-green algae): A Guide for Water Utilities. Water Quality Research Australia Limited: Adelaide, Australia.

A study using MERIS was able to demonstrate detection as low as 10,000 cells/mL (Lunetta et al., 2015). This detection level, although an improvement, is still in the high alert range.

Contact information

Website: http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/

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Rick Stumpf, Ph.D., Oceanographer, NOAA, 301-713-3028 x173, Richard.Stumpf@noaa.gov

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A 4. Lake Huron to Lake Erie Corridor Case Study

Location	**Lake Huron to Lake Erie Corridor, Michigan**
Source Water	U.S. side of St. Clair River, St. Clair Lake, Detroit River
Coordinating Agency	Michigan Department of Environmental Quality
Start Date	2006

System Description

The St. Clair River connects Lake Huron with Lake St. Clair, which is connected to Lake Erie via the Detroit River (Appendix Figure 6). This high traffic corridor is important as a shipping route and a popular recreational area. The west side of the Huron to Erie corridor is in the U.S. (Michigan) while the east side is in Canada (Ontario). The Huron to Erie corridor serves as a water supply for over four million people (Howard, 2007).

"It is our opinion that the Huron to Erie Network is one of the best tools available to maintain safe drinking water" (City of Marysville, Wrubel, 2014).

Appendix Figure 6. Lake Huron to Lake Erie corridor (Morrison, 2006).

The Huron-to-Erie Real-time Drinking Water Protection Network is a spill detection and notification system for water suppliers along the corridor, with near-real-time monitoring data and instantaneous notification. Starting in 2006, this EWS was developed through a partnership between U.S. EPA, the U.S. Department of Homeland Security, the Michigan Department of Environmental Quality, the health departments of Macomb and St. Clair Counties, and 14 drinking water treatment plants (Wrubel, 2014; Lichota and DeMaria, 2009). Funding for the 14 sites was initially received from government grants. The current coverage area includes nine monitoring sites. The decrease in monitoring sites is attributed to limited funding, which is currently supplied through water rates (Wrubel, 2014).

The Huron-to-Erie Real-time Drinking Water Protection Network consists of (1) a water quality monitoring network, (2) a web and database portal and (3) a notification system.

Monitoring Network

Water quality data are collected from nine monitoring stations, located at drinking water treatment plants along the Huron to Erie corridor as illustrated in Appendix Figure 7; plant names in red are no longer included in the network (Wrubel, 2014). The network is equipped with NexSens 5100-iSIC Data Loggers (Fondriest Environmental, Fairborn, OH), 6600 V2-4 Multi-Parameter Water Quality Sondes sensor (YSI Inc., Yellow Springs, OH), Turner Hydrocarbon Fluorometers, Hapsite® ER gas chromatograph – mass spectrometers (GC-MS) (Inficon, Bad Ragaz, Switzerland) and Hach® (Hach, Loveland, CO) total organic carbon (TOC) analyzers (NexSens, 2016).

With near-real-time data transmission, water quality data are logged every 15 to 30 minutes. The monitoring equipment measures pH, temperature, DO, conductivity, turbidity, oxidation reduction potential, chlorophyll, organic carbon, gasoline, diesel fuel, waste oils and other industrial chemicals.

Appendix Figure 7. Lake Huron to Lake Erie drinking water monitoring network (Wrubel, 2014).

Data Management and Interpretation

The Huron-to-Erie Real-time Drinking Water Protection Network database manages water quality monitoring data that is accessible through a secure web portal. Using NexSens iChart software, the online data portal includes tools to view and analyze water quality monitoring data. Interpretation of data includes delineation of alarm conditions, which will vary based on parameter. For example, if industrial chemical detection exceeds either 10%, 50% or 90% of the allowable level, it would be categorized as either an anomaly, a potential spill or a likely spill, respectively (Lichota and DeMaria, 2009). A secondary website for public access to water quality data was also developed.

Communication and Response Network

The system software includes a communication and data sharing network. Based on alarm configuration, as discussed above, water suppliers are notified of adverse water quality conditions for prompt adjustment to plant operations.

Future Development

Potential future plans for the Huron to Erie Drinking Water Protection Network include (Wrubel, 2014):

- Coordination with Canadian agencies to enhance warning system
- Improvement of the flow model
- Integration of incident reporting
- Public outreach and education

Challenges, Insights and Operational Notes

In the configuration of alarm levels, it is important to integrate background levels for proper spill detection (Lichota and DeMaria, 2009). The system has been challenged by the availability of sufficient, sustainable funding and regional organizational coordination. The loss of multiple monitoring stations in the network can be detrimental to the robustness of the EWS.

Contact Information

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City of Marysville, Supervisor of Water/Wastewater Operations, Bari Wrubel, 1535 River Rd. Marysville, MI 48040, (810) 364-8460, bwrubel@cityofmarysvillemi.com.

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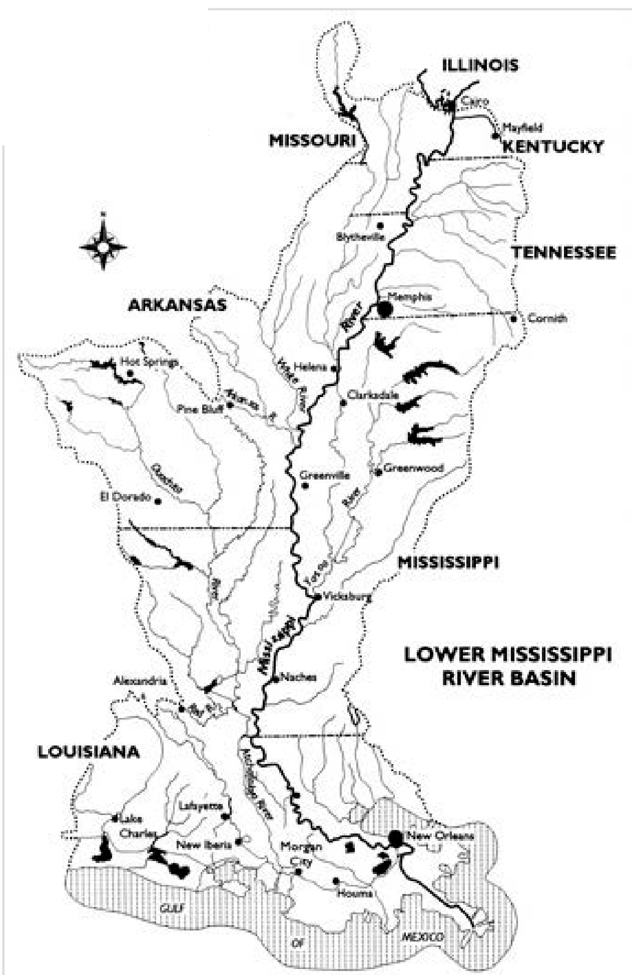
A 5. Lower Mississippi River Basin Case Study

Location	Lower Mississippi River Basin
Source Water	Lower Mississippi River Watersheds
Coordinating Agency	Louisiana Department of Environmental Quality (DEQ)
Start Date	1986

System Description

The Lower Mississippi River runs 954 miles from Cairo, Illinois to the Gulf of Mexico (LMRCC, 2014) (Appendix Figure 8). The Lower Mississippi River Basin spans approximately 105,000 square miles and includes portions of Missouri, Kentucky, Tennessee, Arkansas, Mississippi and Louisiana (USDA, 2013). The Lower Mississippi River is a valuable resource for drinking water, energy production, shipping, industry and recreation.



> *"To combat any threat to drinking water drawn from the river, DEQ, potable water works and industries along the river entered into a cooperative agreement in 1986 to found the Early Warning Organic Compound Detection System (EWOCDS)" (Louisiana DEQ, 2014).*

Appendix Figure 8. Lower Mississippi River Basin (Missouri DNR, 2016).

The Early Warning Organic Compound Detection System (EWOCDS) was implemented in 1986 for the southern-most portion of the Lower Mississippi River, covering Louisiana from Baton Rouge to Plaquemines Parish (Wold, 2015). Over 350 facilities are located along the Lower Mississippi River in Louisiana, where over 1.6 million residents rely on the river as a drinking water supply (Louisiana DEQ, 2014). The original system consisted of nine monitoring stations and was developed with grant funding from U.S. EPA, with subsequent costs covered by the Louisiana Department of Environmental Quality (DEQ) (Louisiana DEQ, 2009). By 2009, after problems with funding and staffing and the withdrawal of some participants from the program, only six monitoring stations were operating (Louisiana DEQ, 2009). Despite a limited budget, the system has remained operational, with one DEQ environmental scientist responsible for management and maintenance. In 2014, the EWOCDS benefitted from a settlement between Exxon Mobil and Louisiana, from which $250,000 was slated for additions and upgrades to the EWS, including new computers and gas chromatographs (Wold, 2015; Louisiana DEQ, 2014). Additionally, funding from the Louisiana Chemical Association was provided to improve consistency throughout the system with the development of standard operating procedures for all monitoring stations (Wold, 2015).

The Lower Mississippi River EWOCDS consists of (1) a partnership between stakeholders, (2) a monitoring network and (3) a notification system.

Monitoring Network

The Louisiana DEQ maintains monitoring equipment, while the sample analysis is the responsibility of the staff at monitoring locations (Louisiana DEQ, 2014). Water quality data are collected from seven monitoring stations. Each location includes a gas chromatograph, with samples collected twice per day at most sites. Two stations have continuous sampling, enabling real-time water quality monitoring. Monitoring stations measure 28 chemical contaminants including halogenated organic compounds, chlorinated hydrocarbons, and trihalomethanes. Results from onsite sample analyses are submitted to the Louisiana DEQ. Monitoring sites as of 2012 are illustrated in Appendix Figure 9, with former sites in gray.

Data Management and Interpretation

Results are reported to the Louisiana DEQ and cataloged in a database. If an incident is detected at a monitoring location, a second sample is used to confirm contaminants. Results are available to the public upon request.

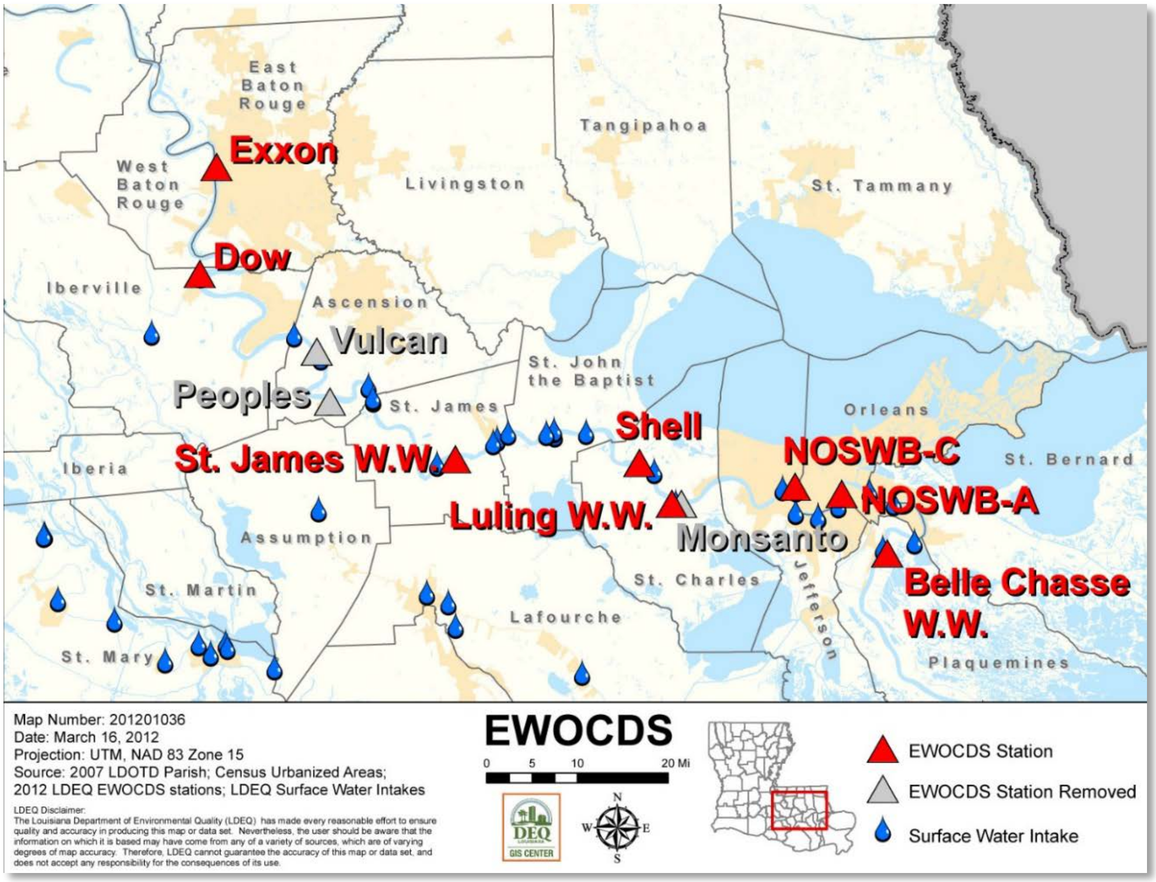
Communication and Response Network

The Louisiana DEQ representative notifies water users if an incident has occurred. The Louisiana DEQ also provides a portal through their website for reporting incidents. Publicly available information does not indicate how EWOCDS data are used during an incident response.

Future Development

Potential future plans for the Lower Mississippi River's EWOCDS include (Wold, 2015):

- System expansion
- Increased participation
- Public outreach
- Website improvements to include public access to water quality summary data



Appendix Figure 9. EWOCDS monitoring locations as of 2012 (Louisiana DEQ, 2012).

Challenges, Insights and Operational Notes

A significant challenge of the EWOCDS is that the program is for qualitative screening (absence or presence) only and not subject to rigorous quality control and quality assurance procedures due to limits on costs and participant expertise. Like other EWSs, the EWOCDS has a limited number of funding sources which, in turn, limit the reach and scope of the program.

Contact Information

Louisiana Department of Environmental Quality, Office of Environmental Compliance, Inspection Division, Tom Killeen, (225) 219-3600, deqinspection@LA.GOV, http://www.deq.louisiana.gov/

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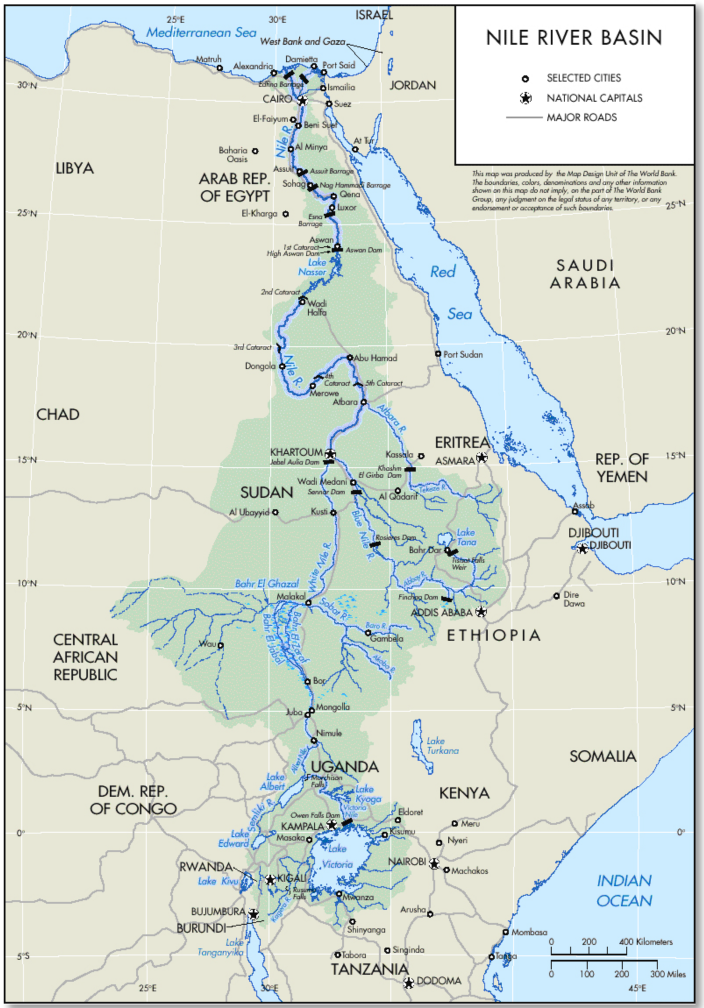
A 6. Nile River Basin Case Study

Location	**Nile River Basin, Egypt**
Source Water	Nile River Watershed
Coordinating Agency	Ministry of Water Resources and Irrigation, National Water Research Center
Start Date	2008

System Description

The Nile River runs 4,160 miles from the Kagera Basin to the Mediterranean Sea (Nile Basin Initiative, 2016). Spanning approximately 1.24 million square miles, the Nile River Basin is home to 238 million people and includes portions of 11 countries including Burundi, Democratic Republic of the Congo, Egypt, Ethiopia, Eritrea, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda (Nile Basin Initiative, 2016) (Appendix Figure 10). The Nile River is a valuable resource for drinking water supply, agriculture, transportation, recreation and industry.



> *"The implemented real time water monitoring and reporting system allows senior water managers to protect the integrity of Egypt's vital water resources, as well as, report the suitability of water for designated beneficial water uses." (Khan et al., 2011).*

Appendix Figure 10. Nile River Basin (World Bank, 2000).

The Nile River Basin Early Warning System was developed with funding through North Atlantic Treaty Organization's (NATO's) Science for Peace Program with coordination from Egypt's Ministry of Water Resources and Irrigation, National Water Research Center. The EWS consists of (1) a monitoring network and (2) an internal database portal.

Monitoring Network

The monitoring network consists of eight monitoring sites along the Nile River in Egypt. Monitoring stations include the following equipment: Hach Hydrolab multi-parameter probe, data logger, weather station and a potentiometer. Real-time water quality monitoring equipment measures pH, DO, temperature, conductivity, ammonia and nitrate at 15 minute intervals. The data are collected with an automated data retrieval system hourly (Khan et al., 2011).

Data Management and Interpretation

Data retrieved hourly from real-time monitoring stations are collected, stored and analyzed in order to produce graphs for assessing water quality changes. Data are accessible through an internal web portal.

Communication and Response Network

Based on the information in Khan et al. (2011), the system includes near real-time data communication. The users can access the data portal to assess water quality changes and take any necessary corrective action.

Challenges, Insights and Operational Notes

Prior to the implementation of this EWS, water quality monitoring on the Nile River in Egypt consisted primarily of grab samples which, while effective, are not conducive to prompt detection and response (Khan et al. 2011). The implemented EWS has the potential for multiple applications as a tool for integrated water resources management in the Nile River Basin.

Future

Current water related initiatives of the Nile Basin Initiative appear focused on flood, drought and watershed management.

Contact Information

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A 7. Ohio River Basin Case Study

Location	**Ohio River Basin**
Source Water	Ohio River
Coordinating Agency	Ohio River Valley Water Sanitation Commission (ORSANCO)
Start Date	1977

System Description

The Ohio River runs 98 miles through 20 locks and dams from the confluence of the Allegheny and Monongahela Rivers in Pittsburgh, Pennsylvania, to the Mississippi River in Cairo, Illinois. The Ohio River Basin is home to approximately 25 million residents and spans 203,940 square miles through parts of 11 states (Brosnan, 1999; ORSANCO, n.d.). The river and its tributaries are not only valuable resources as drinking water supplies, but also for transportation, agriculture, industry and recreation.

The Ohio River Valley Water Sanitation Commission (ORSANCO) is an interstate commission with representatives from eight states and the federal government that was created to abate and prevent pollution in the Ohio River. An overarching goal for ORSANCO is to contribute to improved water quality for drinking water, industrial water, recreational uses and for maintaining a healthy and diverse aquatic ecology (Brosnan, 1999). ORSANCO was established in 1948 and maintains an organics detection system (ODS) to provide its stakeholders with early warning of water quality incidents on the Ohio River. The ODS began with seven monitoring stations established in 1977 in response to a large carbon tetrachloride spill on the river. Currently, it consists of 16 water quality stations at water treatment plants and industries along the river (Schulte, 2014). Samples from these stations are tested at least daily for 30 analytes (Schulte, 2014). In addition to the ODS, ORSANCO's EWS includes self-reporting from industries and rivers users, and a communications network of drinking water utilities and industries along the river (Gullick et al., 2003).

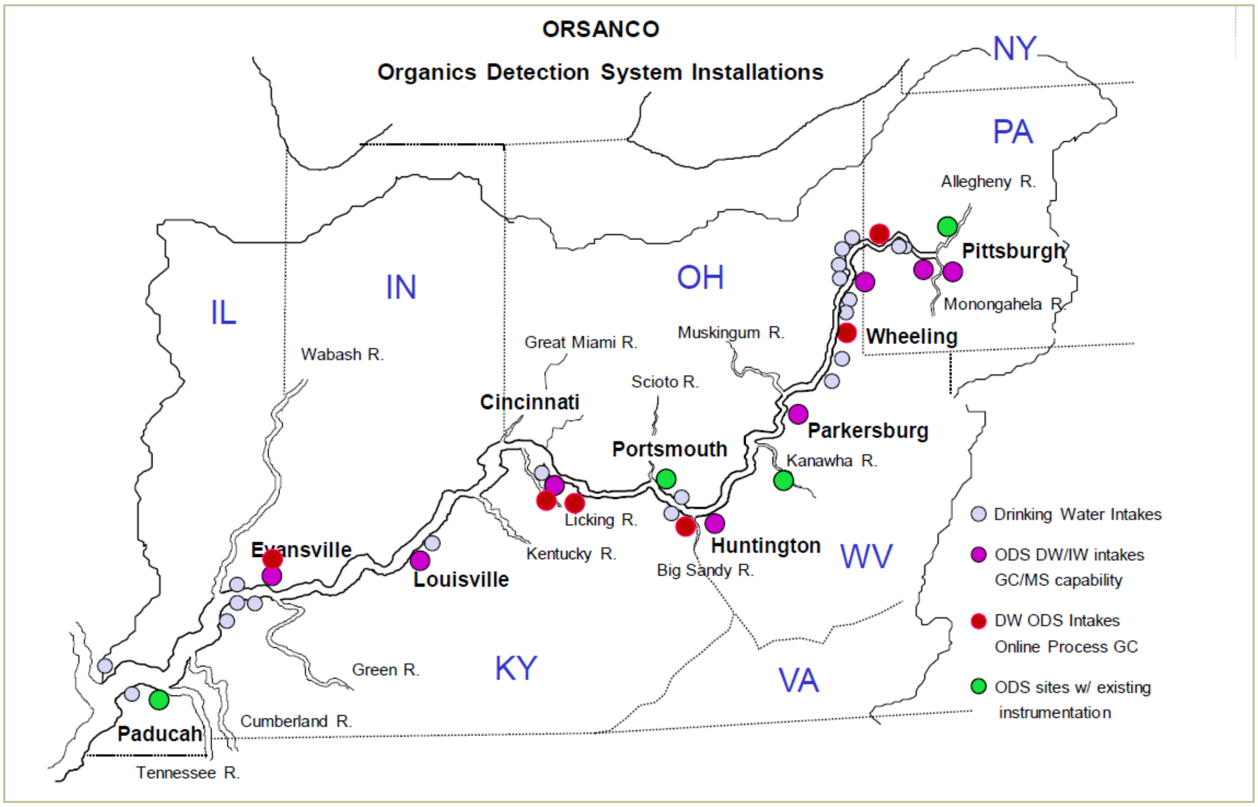
Monitoring Network

The 16 water quality monitoring stations use purge and trap gas chromatographs that are able to detect and track spills (Gullick et al., 2003) (Appendix Figure 11). The stations use a variety of detector technologies, including gas chromatography with flame ionization and photoionization-Hall electrolytic conductivity detectors, to test for the following 30 purgeable organic compounds (Gullick et al., 2003; Schulte, 2014):

- Methylene chloride
- 1,1 Dichloroethylene
- 1,1 Dichloroethane
- Chloroform
- 1,1,1 Trichloroethane
- Carbon tetrachloride
- Benzene
- Trichloroethylene
- 1,2 Dichloropropane
- Dichlorobromomethane
- Toluene
- Tetrachloroethylene
- Dibromochloromethane

- Ethylbenzene
- Chlorobenzene
- Styrene
- Bromoform
- 1,3 Dichlorobenzene
- 1,4 Dichlorobenzene
- 1,2 Dichlorobenzene
- Acrylonitrile
- 1,2 Dichloroethane
- Trans-1,2 Dichloroethylene
- Cis-1,3 Dichloropropene
- Trans-1,3 Dichloropropene
- Hexachlro-1,3-butadiene
- 1,1 2,2 tetrachloroethane
- Trichlorofluoromethane
- Napthalene

A system upgrade that began in 2009 provided updates to equipment, communications and software (ORSANCO - Organics Detection System - ODS, n.d.).



Appendix Figure 11. ORSANCO ODS monitoring locations (Schulte, 2014).

Data Management and Interpretation

ORSANCO's ODS stations follow a common sampling procedures manual and results are reported on at least a weekly basis (Gullick et al., 2003). The system upgrade that began in 2009 included automated detection notification, updated data management architecture, a water quality data website and automated data screening (Organics Detection System, 2011). Data from 1994-2003 are available on ORSANCO's Organics Detection System web page as a Microsoft Access database download.

To further characterize spill incidents, ORSANCO developed a set of models to estimate travel time and plume concentration. These models use the U.S. Army Corps of Engineers (USACE FLOWSED model to calculate travel time and the USGS's Branched Lagrangian Model Transport to estimate water quality (Gullick et al., 2003). Trained staff run the ODS sampling programs as well as the travel time and water quality models, which can ideally be implemented within one hour of notification of a spill (Gullick et al., 2003).

Communication and Response Network

In addition to coordinating sampling, travel-time modeling and other spill characterization efforts, ORSANCO coordinates communications for spill incidents affecting the Ohio River. Incidents can be reported from industries, river users or the National Response Center. ORSANCO's communications system consists of an electronic bulletin board and direct phone or fax communications with water utilities, water-dependent industries and state and federal agencies (Gullick et al., 2003). The 2009 ODS upgrade added short message service (SMS) text message, voicemail and email notification options for event detection notification (Organics Detection System, 2011). An annual emergency response directory is published as a service to its members and stakeholders.

Future Development

ORSANCO continues to plan improvements to its ODS operations to increase its ability to detect, characterize, communicate and coordinate responses to major water quality incidents on the Ohio River. Current ideas include integrating the spill model into a Geographic Information System (GIS) platform, adding contaminant source data, links to material safety data sheets and integration with health effects and treatment data. An emerging significant water quality challenge for the Ohio River is cyanobacteria and ORSANCO has initiated efforts for addressing this concern through monitoring and regional cooperation. Obstacles in that effort will be extensive monitoring required for characterizing the watershed and Ohio River as well as the need to develop predictive models.

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A 8. Susquehanna River Basin Case Study

Location	Susquehanna River Basin
Source Water	Susquehanna River Watersheds
Coordinating Agency	Susquehanna River Basin Commission (SRBC)
Start Date	2003

System Description

Spanning 27,510 square miles in parts of Pennsylvania, New York and Maryland, the Susquehanna River Basin is home to more than four million residents (SRBC, 2013a) (Appendix Figure 12). The Susquehanna River runs 444 miles from Cooperstown, New York to the Chesapeake Bay, and serves as a water supply for over 20 water systems in New York, Pennsylvania and Maryland with an associated population of more than 2.5 million (Gullick et al., 2004, 2006). Water in the region is a valuable resource not only for the provision of drinking water, but also for agriculture, industry, energy development and recreation.

"…A framework for innovative partnerships and protocols for fostering communication and data sharing among water suppliers, state/local agency personnel, and the emergency response community for the purpose of enhancing drinking water protection efforts" (SRBC, 2012).

Appendix Figure 12. Susquehanna River Basin EWS (SRBC, 2012).

The Susquehanna River Basin Commission (SRBC) led the development of the Susquehanna River Basin EWS for the protection of water users dependent on the Susquehanna River. Implemented in 2003, the EWS coverage area initially focused on the 12 Pennsylvania water systems with intakes on the main stem of the Susquehanna River, since the system was largely funded by the Pennsylvania Department of Environmental Protection (Gullick, 2004). With support from New York State, the EWS was extended in 2006 to include the New York section of the Susquehanna River Basin (SRBC, 2012). As the coordinating agency, the SRBC manages the EWS, under the advisement and guidance of the water suppliers, environmental protection agency personnel and emergency responders who comprise the stakeholder group. The current coverage area of the EWS includes water suppliers serving approximately 700,000 people (SRBC, 2013b).

The Susquehanna River Basin EWS consists of (1) a monitoring network, (2) a web and database portal and (3) a communication and data sharing network.

Monitoring Network

Water quality data are collected from nine monitoring points including water quality monitoring of pH, temperature and turbidity with real-time data transmission. At four of the monitoring points, TOC is monitored, while conductivity and DO are also measured at some locations (SRBC, 2012). Monitoring points, located throughout the basin, are shown with green markers in Appendix 11.

Data Management and Interpretation

The Susquehanna River Basin EWS database manages water quality monitoring data that is accessible through a secure web portal. Online tools enable water suppliers to access and analyze real-time water quality monitoring data. Features of the tools include a mapping tool for visualizing real time water quality data and a time-of-travel tool for estimating contaminant dispersal times. The web interface also provides discharger information and contact information for emergency responders.

Communication and Response Network

The coupling of the water quality monitoring network with the SRBC's communication and data sharing network enables access to the real-time monitoring data as well as important water quality data collected by other agencies. For example, the PA DEP has monitoring stations along the river. If an incident or irregular water quality is detected, the PA DEP notifies other water users through the communication and data-sharing network. Water quality information is shared between water suppliers in the same manner. The advanced notice of irregular water quality from spills or other fluctuations (e.g., natural variation in water chemistry), enables timely adjustment of operations at water treatment plants.

Future Development

In addition to the Susquehanna River Basin EWS for drinking water suppliers, the SRBC has developed multiple additional programs to protect and manage Susquehanna River Basin water resources including activities related to source water protection, low flow monitoring, flooding, stormwater runoff and mine drainage, to name a few. The SRBC also implemented and manages an EWS to detect potential contamination from natural gas drilling activities in the smaller rivers and streams of the Susquehanna River Basin in parts of Pennsylvania and New York. Developed in 2010, the Remote Water Quality Monitoring Network (RWQMN) consists of 59 monitoring stations, with real-time measurements of pH, temperature, DO, conductivity and turbidity; nutrients, metals and other constituents of interest are also measured four times per year (SRBC, 2015).

Challenges, Insights and Operational Notes

One challenge for the Susquehanna River Basin EWS is the need for a reliable and sustainable funding structure to operate, maintain, expand and improve the EWS. While state agencies assisted with start-up funding, the SRBC has been responsible for ongoing costs. Despite this challenge, the success of the system can be attributed to systematic and gradual approach; starting small with a limited number of stations and parameters, the system avoided over-extension (Gullick, 2006).

Contact Information

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A 9. Upper Mississippi River Basin Case Study

Location	**Upper Mississippi River Basin**
Source Water	Upper Mississippi River Watersheds
Coordinating Agency	Upper Mississippi River Basin Association (UMRBA) and U.S. EPA, Region 5
Start Date	2003

System Description

The Upper Mississippi River (UMR) runs 1,300 miles from Lake Itasca in Minnesota to Cairo, Illinois, with intakes for more than 20 public water suppliers along the river (UMRBA, 2016). The UMR Basin spans approximately 189,000 square miles in parts of Minnesota, Wisconsin, Iowa, Illinois and Missouri and is home to more than 30 million residents (Swanson, 2012) (Appendix Figure 13). The UMR is a valuable resource for drinking water systems, as well as power plants, industry, transportation, agriculture and recreation.

> *"UMR-based public water suppliers, industries, and other partners have supported efforts to establish an "early warning monitoring network" on the UMR which would serve to provide advanced warning of a spill event via continuous monitoring installations" (UMRBA, 2014).*

Appendix Figure 13. Upper Mississippi River Basin (U.S. Fish and Wildlife, 2015).

Early development of the UMR Basin Early Warning Monitoring Network (EWMN) was organized by American Water, a water utility in the region. With assistance from U.S. EPA Region 5, further development was led by the Upper Mississippi River Basin Association (UMRBA). UMRBA was developed as a joint effort between UMR Basin states for the management of the water resources in the UMR Basin. UMRBA is comprised of governor-appointed representatives from Illinois, Iowa, Minnesota, Missouri and Wisconsin (UMRBA, 2016). A pilot monitoring station was operated from 2003-2007 in Rock Island, Illinois. The funding was provided by U.S. EPA and in-kind (non-monetary) assistance (UMRBA, 2007; Swanson, 2012). Following the pilot project, the U.S. EPA became the primary coordinating agency, with principal funding from the Regionally Applied Research Effort (RARE) grant. Partnerships, collaborative efforts and the monitoring network were subsequently expanded. The resulting collaboration includes the following partners: U.S. EPA, USACE, Shaw

Environmental, other state and federal agencies, water utilities, the UMR Spills Group[1], UMRBA, universities and other stakeholders.

The UMRB EWMN consists of (1) a water quality monitoring network, (2) a web and database portal and (3) a notification system.

Monitoring Network

The single station pilot system operated from 2003-2007 in Rock Island, Illinois, consisted of a YSI Model 6600 Sonde sensor, which measured DO, chlorophyll, oxidation reduction potential, pH, temperature, conductivity and turbidity. Online toxicity monitors were also piloted with biomonitoring (Swanson, 2012).

The monitoring network includes six real-time monitoring stations that consists of a YSI probe, a s::can Spectrolyser spectrometer, bi-valves and sensors, and a computer interface. The YSI probe measures temperature, conductivity, DO, pH and turbidity. The s::can Spectrolyser spectrometer measures turbidity, nitrate, TOC and DOC. Bi-valves equipped with sensors serve as online toxicity monitors, with gape behavior used as a toxicity indicator.

Data Management and Interpretation

During the operation of the pilot system, the USACE online data system, River Gages, was used for data collection and management.

Communication and Response Network

Notification of adverse water quality is delivered through e-mail alerts, enabling timely adjustment of operations at water treatment plants. In the discussion of biomonitoring, Allen et al. (2014) presented a tiered response model; upon detection of a change in water quality, a sample is collected, and a positive bioassay result leads chemical analysis followed by an appropriate remedial/regulatory response.

Future Development

Goals of the UMRB EWMN include (Swanson, 2012):

- Maintaining the existing monitoring network
- Securing stable and sustainable funding
- Addressing database needs
- Considering improvements to the bio-monitoring algorithm
- Maintaining and improve partnerships

Challenges, Insights, and Operational Notes

The pilot project highlighted the need for sustainable funding over the long-term as well as challenges with respect to organizational coordination. With a multitude of stakeholders and a wide-ranging coverage area, for the success of the UMR EWMN, a leading organization must act as the coordinating agency (UMRBA, 2007). Similarly, Allen et al. (2014) stressed the importance of collaboration given the project's scale.

[1] The UMR Hazardous Spills Coordination Group includes members from US EPA, USCG, USACE, the U.S. Fish and Wildlife Service, the Upper Mississippi River Basin Association (UMRBA), as well as environmental and public health agencies in Illinois, Iowa, Minnesota, Missouri, and Wisconsin (UMRBA, 2014).

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