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Water Expert: a conceptualized framework for development of a rule-based decision support system for distribution system decontamination

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Abstract

Significant drinking water contamination events pose a serious threat to public and environmental health. Water utilities often must make timely, critical decisions without evaluating all facets of the incident, as the data needed to enact informed decisions are inevitably dispersant and disparate, originating from policy, science, and heuristic contributors. *Water Expert* is a functioning hybrid decision support system (DSS) and expert system framework, with emphases on meshing parallel data structures to expedite and optimize the decision pathway. Delivered as a thin-client application through the user's web browser, *Water Expert*'s extensive knowledgebase is a product of inter-university collaboration that methodically pieced together system decontamination procedures through consultation with subject matter experts, literature review, and prototyping with stakeholders. This paper discusses development of *Water Expert*, analyzing the development process underlying the DSS and the system's existing architecture specifications.

1 Introduction

Decontamination decisions made following contamination events for water distribution networks (WDNs) are a complex entanglement of empirical practices that are selected through heuristic solution processes. Oftentimes in such events, a lack of synthesized information does not afford the decision maker with the ability to rationally determine the optimum remediation and recovery strategy. The data needed in the decision making progression can be supplied through field observations, mathematical models, regulatory requirements, and organizational policy, varying both spatially and conceptually, as science and policy from the local, state, and federal scales are pooled to produce conclusions. Coalescing these diverse sources of data into usable information presents a challenge. Thus to make a timely decision, the managers of WDNs are unlikely to take into account all characteristics of the emergency situation. It is in this regard that web-delivered information systems, driven by artificial intelligence (AI) such as expert systems, provide a means by which to supply the decision maker with recommendations at any location, and base these on a compilation of divergent data sources within an integrated decision support system platform. The *Water Expert* system framework, a hybrid DSS with expert system capabilities, provides such a means. Developed by a consortium of universities, this application provides integrated decision making tools that are driven by all of the identified data inputs and presented to the user through their local web browser. Integrated with KYPipe's Network Decontamination Model (NDM), data can be acquired from third party applications, uploaded into *Water Expert* via the internet, and used to drive *Water Expert* recommendations and actions.

Water Expert provides recommendations for decontamination of WDNs using regulatory requirements, manuals of practice, academic and trade association journals, and industry-established procedures, obtained from a series of tabletop, technology demonstration, and technology deployment workshops hosted by the investigating consortium. This system can be dynamically augmented to include other knowledge domains such as local and state regulations as needed. Further, additional third-party applications can similarly be linked into *Water Expert*, either replacing or augmenting its standard toolset.

This paper describes the groundwork for the *Water Expert* concept. Primarily, the current methodology of decision making during WDN emergency operations, how *Water Expert* augments this process, and the technical and contextual composition of *Water Expert* are described. A case study with a small WDN will demonstrate the system's current capacity. Finally, a discussion of the future vision for the *Water Expert* platform will follow.

2 Literature review

Critical to successful water system recovery following a contamination event, decontamination has repeatedly been highlighted as a significant issue for the water sector.

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This is evidenced by the numerous working groups and councils that have strategized and formulated the most appropriate courses of action (Water Sector Coordinating Council, 2007; Water Sector Decontamination Workshop, 2008). In addition governmental agencies such as the US Environmental Protection Agency (USEPA), and trade associations such as the American Water Works Association (AWWA) and the Water Research Foundation (WRF), develop and maintain guidance documents (USEPA 2012; Water Research Foundation, 2009), case studies (USEPA, 2008; Murray et al., 2010), and tools (Sandia National Laboratories, 2010; USEPA, 2013a, 2014b, c) that are intended to enhance water infrastructure resiliency to contamination events.

In particular, the USEPA has published a series of guides, collectively known as the Response Protocol Toolbox (USEPA, 2003a, c, d, e, f, 2004b, c, d), for addressing security and protection of the drinking water and wastewater sectors and actively maintains the Threat Ensemble Vulnerability Assessment (TEVA) program (Murray et al., 2004). However, synthesized information for water systems to make informed decisions regarding decontamination of compromised drinking water systems is lacking, as disparate sources of information cloud the resolution process. No comprehensive software application currently exists to guide utility managers and planners through the process of recovering after a contamination event in a distribution system. Therefore, a significant disconnect remains between the numerical modeling applications, such as EPANET2, and taking the appropriate course of action during contamination episodes.

Appropriate decontamination procedures are further contorted by the actions incorporated at the individual utility level, through site-specific Vulnerability Assessments (USEPA, 2002a, c), Emergency Response Plans (ERPs) (USEPA, 2003b, 2004a), and Sanitary Surveys (USEPA, 1995, 2001). Vulnerability assessments include a review of pipes and constructed conveyances; physical barriers; water collection, pretreatment, treatment, storage and distribution facilities; electronic, computer or other automated systems which are utilized by the public water system; the use, storage, or handling of various chemicals; and the operation and maintenance of the system. ERP's include plans, procedures, and identification of equipment that can be implemented or utilized

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in the event of a terrorist or other intentional attack on the public water system. The ERP also includes actions, procedures, and identification of equipment which can prevent or significantly lessen the impact of terrorist attacks or other intentional actions on public health and safety and the supply of drinking water provided to communities and individuals. Sanitary surveys review a water system's source water (identifying sources of contamination using results of source water assessments where available), facilities, equipment, operation, maintenance and monitoring compliance in order to evaluate the adequacy of the system, its sources and operations, and the distribution of safe drinking water. The findings from these efforts at the local level are paired with information produced by government and trade associations and provided to output decision models for contamination events.

Artificial intelligence (AI) has successfully been applied to bridge the gap between data acquisition and heuristic decision making. AI has been used extensively in the industrial sector (Fonseca et al., 2003; Delen and Pratt, 2006; Moynihan, 2004; Moynihan et al., 2006) and business community (Ahn et al., 2000; Nemati et al., 2002; Bahrammirzaee, 2010; Shen et al., 2011) to turn data into knowledge. AI application has also migrated into additional disciplines, including the water industry, where it has been demonstrated as an aid to modeling water quality (Panda et al., 2004; Purkait et al., 2008; Kisi et al., 2013) estimating water quantity (Nourani et al., 2012), predicting wastewater treatment performance (Rene, 2008), and optimizing distribution system design (Suribabu and Neelakantan, 2006).

Expert systems, a form of AI, have been used to provide recommendations for sensor placement in water distribution networks (Chang et al., 2012a, b), to improve distribution system performance (Sandeep and Rakesh, 2011), and for flood control (Karbowski et al., 2005).

In this optic, The University of Alabama, Western Kentucky University, The University of Kentucky, the University of Missouri, and the University of Louisville teamed together and developed an analysis and decision support system, powered by an expert system shell, that provides guidance to water sector owners and operators for the

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decontamination of water systems after a significant chemical or biological agent is propagated within their distribution system.

This tool, the Water Distribution Network Decontamination Decision Support System (WDNDDSS), or *Water Expert*, provides guidance to local, state, and regional water system owners and operators during their initial response and subsequent decision making regarding contaminated water systems. The system accomplishes this by enveloping and incorporating information acquired through literature reviews, tabletop exercises, and technology demonstration and deployment workshops conducted by each participating university into a knowledgebase. *Water Expert* includes both graphical tools and user-assisted menus for helping water system personnel select the appropriate course of action relative to the nature and extent of contamination. This tool uses the Network Decontamination Model (NDM), a modification to the hydraulic modeling software KYPipe, to: identify what valves need to be closed to isolate a particular pipe, or section of pipes, in the event of contamination; calculate the associated volume of water that may have to be remediated; identify hydrants that are connected to the contaminated section; and determine whether closing different valves will result in additional pipes becoming isolated and/or the pressures at different parts of the system being adversely impacted (KYPipe and University of Kentucky, 2012; KYPipe, 2014).

Water Expert then generates a local fact base derived from the user and compares this to the knowledgebase using a pattern matching, inference engine. Interaction with this system is performed through an online Content Management System (CMS), Drupal 6 (Drupal, 2008), with an embedded expert system shell, C Language Integrated Production System (CLIPS) (CLIPS, 2013). Water Expert generates warnings regarding the public and environmental health effects of a contaminant and if the contaminant notifications exceeds both drinking water and source water concentrations. Additionally, it offers recommendations for the most effective treatment technologies, including detailed procedures and recommendations and provides fact sheets on common contaminants.

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The tool has the ability to integrate third party applications, including EPANET2 and Geographic Information System (GIS) data and provides the adaptive extensibility needed to refine the system to meet the needs of individual utilities.

3 Methodology

Water Expert is a product coalesced from research conducted at six water research and development centers at five participating universities; Research by the participating entities eventually amalgamated and comprised the architecture of WDNDDSS. Figure 1 illustrates the flow of the system.

The Water Resources Research Center and the Community Policy Analysis Center at the University of Missouri conducted a literature review that would elicited a large portion of the Knowledgebase of Guidance Rules depicted in Fig. 1. The CIR at the University of Louisville conducted a series of tabletop exercises that examined the decision-making practices of key agencies involved in decontamination, further feeding the Knowledgebase. The KWRRI at The University of Kentucky and KYPipe partnered to develop the Network Decontamination Model (NDM), where GIS data and KYPipe were integrated to provide visualization and analysis tools to feed data into Water Expert. These projects were then coalesced within the WDNDDSS or *Water Expert* system framework by the EI at The University of Alabama and CWRS at Western Kentucky University, to provide an integrated platform with which utilities could make timely and informed decisions on how to best decontaminate their distribution system. CWRS and EI then hosted a series of technology demonstration workshops in which the final product was examined by utility administrators and regional planners. A subsequent round of technology deployment workshops were then hosted to demonstrate the final product at three participating utilities.

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3.1 Literature review and state of the art decontamination report

An extensive literature review of government and research databases was conducted by the Water Resources Research Center and the Community Policy Analysis Center at the University of Missouri in which the current methodology and technology available for decontaminating drinking water systems was appraised and incorporated within *Water Expert*, producing a robust knowledge domain for validating decontamination strategies.

With the inception of the Bioterrorism Act of 2002 and the Homeland Security Presidential Directive 7 (HSPD 7), the USEPA was placed in charge of facilitating resilient water infrastructure (US Department of Homeland Security, 2003; USEPA, 2002b) this led them to produce a series of guidance documents and tools for utilities to utilize in order to improve their contamination resiliency, forming the girth of fused information currently available for contamination prevention and recovery. These products included detailed systematic methodologies for response and recovery during contamination events (USEPA, 2003a, c, d, e, f, 2004b, c, d), guidelines for preparing Emergency Response Plans (USEPA; 2003b, 2004a), procedures for preparing vulnerability assessments (USEPA, 2002a, c), and a database of contaminants that pose significant threat to water systems (USEPA, 2013a). In particular, Module 6 of the USEPA Response Protocol Toolbox provided a consolidated table of treatment technologies and their effectiveness in treating broad classifications of contaminant species. A variation is presented in Table 1 (USEPA, 2004c).

Review of publicly available research databases, such as *Academic Search Premier* and *Scopus*, provided additional detailed knowledge concerning the decontamination process. Each relevant literature item in this search was reviewed and condensed into a summary. This search found nearly 900 pieces of relevant literature with information on technologies and methodologies pertinent to decontamination of a water system.

Overall, results indicated that the course a utility takes towards decontamination will likely depend upon factors including contaminant characteristics, distribution system

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characteristics, volume of affected water, extent of the contamination, and resources available for response. *Water Expert* was designed with these decision making characteristics in mind.

3.2 Tabletop exercise

To gain perspective on the relevant decision points in making an informed decontamination decision, a workshop involving utilities, emergency responders, and other stakeholders was hosted and conducted by the CIR at the University of Louisville. These were modeled on the tabletop exercise format developed by the Homeland Security Exercise and Evaluation Program (HSEEP) (US Department of Homeland Security, 2013) and focused explicitly on recovery of the distribution network. A centralized mind-mapping theme was chosen to organize the thoughts created during the exercise and a mind-mapping expert was brought in to effectively transfer the interconnectivity and centralized themes of the discussions (Margulies and Maal, 2002). As the decision making activities during the recovery process are non-linear, this mind-mapping format translated well as an approach to organizing the thoughts that were generated during the tabletop exercises (Stephens and Hermus, 2007).

Participants were allowed to engage amongst themselves and with CIR researchers within an exercise that examined the decision making process which would occur during a simulated contamination event, suggested through consultation with the participating water agencies. Participants were guided to a point in the contamination narrative in which the contaminant was contained and the situation had stabilized and were then asked to generate a set of questions that must be answered in order to effectively make the correct decision. These questions were to be considered the critical decision points that were elicited from the exercise. Table 2 is a summary table of these decision points categorized by general areas of concern. The group's mind map is presented in Fig. 2.

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3.3 Network Decontamination Model (NDM)

To address the spatial issues related to potential contamination events, the NDM was created as a module to the widely used KYPipe hydraulic modelling software, in co-operation with the KWRRI at the University of Kentucky. The NDM is a graphical utility that can generate a schematic of a utility's distribution system using preexisting geographic information system (GIS) data to analyze the extent of contamination within the distribution network.

Generation of NDM models has been prototyped using the Kentucky Infrastructure Authority's (KIA's) preexisting online portal of water infrastructure data, the Water Resources Information System (WRIS) (Kentucky Infrastructure Authority, 2013). This database includes GIS information on pipelines, water tanks, water treatment plants, water meters, and pump stations. A direct linkage to this repository was established within the NDM that allows the user to seamlessly download and generate a model for their distribution system. Figure 3 is an example NDM network model.

Functionally, the NDM provides the user with the ability to examine the spatial distribution of valves and hydrants, important for either isolating the contaminant or for ex-situ remediation of the network. Users can alter contaminant spread through opening and closing the valves and hydrants. Additionally, the locations of critical customers, such as hospitals and schools, are visualized through the use of icons and backdrop maps (Fig. 4).

Once a full contamination event is conceptualized in the NDM, the model calculates the volume of contaminated water, summarizes the valves and hydrants in the contamination area, identifies the age and material of pipe in the contamination area, and identifies the hydrant with the lowest elevation, important if the system is to be flushed. These outputs are then reported to the user, where they can either use the data independently or export it for use within *Water Expert*. Figure 5 is an example of hypothetical contamination event, created using the NDM (KYPipe and University of Kentucky, 2012).

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3.4 Rules Based Decision Support Tool (RBDST)

The knowledgebase in *Water Expert* was constructed using the guiding principles of knowledge engineering. According to McCorduck and Feigenbaum (1983), this philosophy takes the knowledge associated with complex problem-solving abilities, normally requiring an advanced level of human expertise, and converts it into a computerized format. The process of performing this conversion includes four steps: (1) information is gathered using literature reviews, workshops, and seminars; (2) information is extracted from these sources; (3) information is compounded into a taxonomical structure that comprises a knowledgebase; and (4) the knowledgebase is integrated into computerized modelling or simulation environment for functionality and additional knowledge extraction. In *Water Expert*, the knowledgebase was created by CWRS at Western Kentucky University and the EI at The University of Alabama. It unites data gathered during the initial literature review, state of the art decontamination report, tabletop exercises, and through discussions with an external advisory board of industry, regulatory, and trade association representatives. These data are held within a MySQL relational database management system (RDBMS) (Oracle, 2014) and brought to the user through the Drupal 6 CMS (Drupal, 2008). Rules and facts that comprise the knowledgebase are driven by the CLIPS inference engine (CLIPS, 2013).

3.5 Technology deployment and implementation workshops

The prototype version of *Water Expert* was evaluated at four deployment workshops, hosted by CWRS officials from Western Kentucky University, KWRRI staff from the University of Kentucky, and KYPipe representatives. Participants included water utility personnel, emergency preparedness representatives, public health officials, regional planners, and regulators. Training materials were created to assist participants in learning the software's functionality and each was guided, step-by-step, through usage of the *Water Expert* and the NDM. Participants were asked to fill out two separate evaluation forms (one for the overall *Water Expert* system, and one for the NDM) to solicit

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feedback on the presentation, the presentation materials, and the features of *Water Expert* Following each workshop.

Subsequent to the technology demonstration workshops, project personnel used the feedback gathered therein to refine the software and ultimately develop a revised version of the prototype *Water Expert*. This product was then launched at three utilities who aided the research team in conceptionalizing plausible contamination scenarios for formal validation. These 3 hypothetical contamination scenarios provided further demonstration and evaluation of the software's effectiveness.

4 Outcomes

Water Expert includes both graphical tools and menus that allow the user to select the appropriate course of action relative to the nature and extent of contamination. It is delivered to the user as a remote server application by accessing the web through a preferred browser. The primary target users water utility managers or operators. It is envisioned that academics, regulators, public health officials, emergency preparedness representatives, and local and regional planners may also find *Water Expert* of value. The *Water Expert* code is separated from the core CMS installation and is a PHP modular extension to Drupal 6.

The following sections summarize the functionality of the system. Figure 6 is a system flow chart for the final software product that summarizes its functionality, which was adapted to respond to the decision points presented in Table 2. The. Each of these portals are entrances where the user interacts with the *Water Expert.* They exist on the Drupal 6 CMS, the central hub of interaction with *Water Expert*. User input gathered at these portals becomes "local facts" that are compared against the system-wide "global facts", derived from preceding subprojects, using the CLIPS inference engine. All reports and recommendations are graphically output to the user using the CMS. *Water Expert* is refined through the CMS, providing the extensibility necessary to update and

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expand the knowledgebase, to generate facts and rules on demand for the user, and to engage the expert system inference engine.

Water Expert preliminarily addresses contaminants that are contained within the United States Environmental Protection Agency National Primary Drinking Water Regulations. The concentrations or amount of contaminants that provide warnings and recommendations by *Water Expert* are those believed to have an effect on both human (ATSDR, 2013; USEPA, 2013b) and environmental health (USEPA, 2014a). Technology recommendations are based on findings from the USEPA, concerning treatment effectiveness on specified species of contaminants, as previously depicted in Table 1. Outputs from the NDM are transferred to a CSV file, uploaded into the MySQL RDBMS, and used to generate additional facts, to compare against the knowledgebase, as to whether the contaminated piping material will interact with the contaminant(s) of interest.

4.1 User input

A four-step user-input process is initiated through the CMS on a local web browser (Fig. 6). This process begins with guiding the user through developing a profile of their distribution system including name, administrative contact, address, population served, etc. These "Water System" data are not used by the analysis portion of the current system but are an indexing mechanism to gather information pertinent to the contamination event. Information on the specific contaminant is gathered at the "Contaminant Information" portal where the user provides a detailed review of the contaminants found during the contamination event, including the location and concentration of the contaminant. *Water Expert* allows the user to either enter the network information manually or utilize the NDM. These data are currently used by the system to determine whether network infrastructure will be degraded by the contaminant(s) of concern.

Along the data gathering pathway, facts are generated on demand and are conglomerated at the "Decontamination Scenario" portal. Once this information is submitted, MySQL ports the generated facts to a server-side instance of CLIPS, where pattern

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matching between the “local facts” and “global facts” is executed. Once the system has concluded its analysis, a “Recommendations” page is generated and rendered to the user on the CMS. Here the user in warned of both the public and environmental health concerns, what regulatory exceedances have occurred based upon the given concentration, if the contaminant poses a threat to network materials, and provided a weighted list of treatment technologies to decontaminate the system. Figure 7 is an example of these recommendations.

4.2 Fact and rule creation

Facts are created by both the user (local facts) and site administrators (global facts) through the CMS, providing Water Expert with a guided protocol that facilitates the extensibility required to update and maintain the evolving knowledgebase. Using PHP code and the Drupal Content Creation Kit (CCK) (Drupal, 2013), CCK content types were designed for each type of fact, for example a *Contaminant* content type is used to generate facts on the contaminants of interest. Data entered are then stored in the RDBMS and analyzed and synthesized by PHP into the fact format necessary for the CLIPS inference engine. Rules are also created in a similar fashion and removing facts and rules is also performed through the CMS. It is this mechanism that provides flexibility to update and use knowledge in an expedited manner.

4.3 Training, education and guidance

In order to streamline the knowledge retrieval process and simplify the user interaction process, prescribed pathways have been developed within the CMS with predefined endpoints representing the typical use cases. Fact sheets are provided on all USEPA-regulated contaminants and consist of pre-packaged content, derived from the RDBMS, which can be retrieved with minimal user input through point and click interaction with the CMS. These are designed for rapid access and address specific aspects of a contaminants of concern. Additionally, navigable content, guidance

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documents that are interactive, allows the end-user to peruse information in a self-determined sequence. Information in guidance documents is designed for hierarchical access to increasing detail. Interactive guidance is provided by an installation of GraphViz (GraphViz, 2014), which presents the user with flowchart visualization. Figure 8 is an example of the interactive GraphViz charts that are used to navigate the guidance documents.

5 Case study

In order to illustrate the functionality of the system in its current capacity, envision a city named Anywheretown located adjacent to a major interstate, where the risk of possible chemical spills caused by vehicular wrecks is high. It has been documented in several US states that a large portion of accidents involving hazardous chemical spills involve those with petroleum oils and fuels (Becker et al., 2000; Golla et al., 2012). Therefore a spill, intentional or unintentional, involving gasoline is a plausible scenario.

Assume that such an event occurs and that, insufficient cleanup activities are performed at the spill site, which allow the gasoline to remain within the soil matrix and interact with nearby water distribution system piping. It was demonstrated in Ong et al. (2010) and the American Water Works Association (AWWA) and Economic & Engineering Services, Inc. (2002) that this will cause thermoplastic piping (polyethylene [PE], polyvinyl chloride [PVC], etc.) to degrade and allow the substance to permeate the piping. Assuming that the Anywheretown distribution system is entirely comprised of polyethylene and the piping is relatively new, this degradation process would usually occur on the order of several weeks.

However, for the substance to enter the distribution system, a sufficient drop in pressure at the point of contamination must have occurred. Such a drop in pressure may be the result of: a system ill-prepared to supply fire flow, a part of the system being taken offline which isolates sections of the network from service, system pumps going down, and/or intrusion events (Fleming et al., 2005; Besner et al., 2010). Thus, it is

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assumed one of these events drove the network to zero or negative pressure at the point of injection, allowing the contaminant to permeate the polyethylene piping and enter the distribution system.

The Anywheretown Water Department then begins receiving taste and odor complaints from customers in the general vicinity of the spill location. Testing reveals that Benzene, a major constituent of gasoline is present at a 0.8 $mg\,L^{-1}$ concentration. Unsure of what to do, the Anywheretown decision makers consult the *Water Expert* system about the situation, entering into *Water Expert* the data found in in, categorized by the content type where the information was entered. Water System and Decontamination Scenario information are omitted as they are only used as an indexing mechanism. Network Information was added manually, in lieu of no available network information.

The inputs generate the summarized recommendation in Tables 3–6. These tables demonstrate *Water Expert's* ability to summarize the data found to be critical to the decontamination process by the University of Missouri literature review and the decision points found as part of the tabletop exercises conducted by the University of Louisville.

6 Further research

Present capacity to offer decontamination assistance will be complimented with the development of tools which will perform comprehensive examination of the economic effects of disruptions in water service (Alva-Lizarraga and Johnson, 2012; Gutenson et al., 2013), as well as tools to help utilities develop monitoring and control systems for their distribution network. Supplementary projects are intended to address capacity development issues for infrastructure systems, such as Asset Management and ERP development. Additionally, embedded hydraulic modelling and integrated GIS will be used to expand *Water Expert's* capabilities.

Each individual summary prepared in the literature review is anticipated to be used to extend the knowledgebase of *Water Expert* in the form of facts and rules. These will augment the existing fact and rule base and provide drill down capabilities within *Water*

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Expert for users who desire more descriptive information. An example of this functionality is the system's current ability to recognize the interaction between hydrocarbons, such as diesel and gasoline fuels, with thermoplastic piping.

The system is moving from a web-deployed environment to a localized, enterprise-wide cloud based system, similar to that depicted in Fig. 9. This migration is driven by concerns voiced by utility and trade association representatives who hesitate to place sensitive data in a remote database. Thus, future iterations of *Water Expert* will take advantage of the concept's adaptive nature and will transition to fat-client applications installed on user's local machines and interact with local databases. This new format will be designed to interact with a utility's local databases and supply them with recommendations at an institutional level. Inputs and outputs will be supplied to the system through utility representative's mobile and desktop hardware, facilitating immediate feedback and response among all members of the organization.

7 Conclusions

The functionality of *Water Expert* serves to provide a comprehensive set of tools for which the user can explicitly determine the most viable pathway for decontamination following a contamination event. *Water Expert* does this by generating a local fact base derived from the user and compares this to the knowledgebase of global facts and rules using the CLIPS pattern matching, inference engine. Interaction with this system is performed through an online instance of the Drupal 6 CMS, with an embedded CLIPS expert system shell, which generates public and environmental health warnings, determines if concentrations exceed regulatory limits, and assesses effectiveness of a wide range of commonly utilized treatment technologies. Additionally it provides pre-defined endpoints representing the typical use cases. These currently exist in the form of fact sheets that are provided for all USEPA regulated contaminants and interactive guidance documents that guide the user through the decontamination process.

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The development of this tool has involved most, if not all, key stakeholder groups in every step of the creative process. From the literature review which tapped into the academic and research aspects of the decontamination process, to the series of tabletop and demonstration workshops that provided hands-on opportunities for practitioners in the water industry. The schema has allowed the researchers to identify the critical needs of the industry and align them with the overarching development goals for *Water Expert*. This form of development has created a living application that can grow and adapt with the dynamics of the industry.

Key to the functionality of *Water Expert* is its adaptability. The conceptual framework of the system has allowed researchers to integrate *Water Expert* with third-party applications, like the NDM, which opens the door for more robust coupling of models from an assortment of academic disciplines. Intuitively, with this expansion will come an increase in the data available for the inference engine to process, likely promoting a more attuned set of recommendations. To this end, the functionality of *Water Expert* is also completely independent of any software that it currently utilizes. Thus, while a functional system, the schematic of the system can adapt to any necessary changes that arise.

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Table 1. Technologies used to decontaminate water and their relative effectiveness, adapted from USEPA Module 6: Response and Recovery Guide (USEPA, 2004c).

Technology	Inorganic Chemicals	Microbes	Radionuclides	Non-volatile Organic Chemicals	Volatile Organic Chemicals
Activated Alumina	More Effective	Not Effective	More Effective	Insufficient Data	Insufficient Data
Activated Carbon	Less Effective	Insufficient Data	Less Effective	More Effective	More Effective
Air Stripping	Not Effective	Not Effective	Not Effective	Not Effective	Less Effective
Chloramination	Insufficient Data	Less Effective	Not Effective	Insufficient Data	Insufficient Data
Chlorination	Less Effective	More Effective	Not Effective	Insufficient Data	Less Effective
Chlorine Dioxide	Less Effective	More Effective	Not Effective	Insufficient Data	Less Effective
Coagulation/Filtration	Less Effective	More Effective	Not Effective	Less Effective	Not Effective
Direct Filtration	Insufficient Data	More Effective	Insufficient Data	Insufficient Data	Insufficient Data
Ion Exchange	More Effective	Not Effective	More Effective	Not Effective	Not Effective
Microfiltration/Ultrafiltration	Not Effective	Insufficient Data	More Effective	Insufficient Data	Not Effective
Ozonation	Less Effective	More Effective	Not Effective	Less Effective	Less Effective
Reverse Osmosis/Ultrafiltration	Not Effective	More Effective	More Effective	More Effective	More Effective
Ultraviolet Disinfection	Not Effective	More Effective	Not Effective	Insufficient Data	Insufficient Data
Advanced Oxidation	Less Effective	More Effective	Not Effective	More Effective	More Effective

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Table 2. Summarized decision points critical to response following a contamination event.

General Area of Concern	Decision Points
Contaminant	1. What is the contaminant? 2. Is the contaminant isolated to single site? Or impacting multiple sites? 3. Is the contaminant biological? Is it contagious? 4. What if the contamination event occurs during inclement (freezing temperatures)? 5. Is this contaminant a vehicle for another contaminant? 6. Is the type of contaminant known or unknown? 7. What are the environmental and public health risks with the associated contaminant?
Laboratory Support	1. What laboratory support will be needed and how will this be coordinated? 2. Will local laboratory have the capacity to meet testing demands? 3. If additional facilities are needed, how will they be selected? Overseen? 4. Where can processes and procedures for coordination of laboratory analytical support be found? 5. What EPA laboratory network member laboratories may be available to provide analytical support and how can these laboratories be identified?
Recovery	1. When does response end and recovery begin? 2. What facilities and/or activities are most critical and require immediate attention at the conclusion of response activities? 3. What tools are available to assist in identification of contaminants, water-treatment methods and infrastructure decontamination? 4. What procedures are in place to expedite the recovery process and return to normal business operations? 5. When is the drinking water considered safe and how will the public be convinced that it is safe? 6. What is the recommended sampling protocol? 7. How will the utility ensure that the backflow does not re-contaminate the system? 8. What are the economic impacts of long-term outages? 9. If the contamination was intentional, how does that change the response and responsibilities? 10. At what point would you have a debriefing to identify lessons learned?

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Table 2. Continued.

General Area of Concern	Decision Points
Critical Customers	1. Have the vulnerable customers been identified? Do you have appropriate contact information for them? 2. How will impacted critical care customers be handled during long-term outages? Evacuation? Shelter in place? 3. What if a school is impacted? Alternative schools? 4. What are the short-term and long-term health effects of the contaminant on humans?
Infrastructure	1. Do we know the pipeline material affected by the contaminant? 2. What is the permeability of the pipeline? 3. What is the age of the affected pipeline? 4. Is there information on the contaminant's short-term and long-term impact on pipeline materials, valves and gaskets? 5. Is there information on the contaminant's interactions with permeable materials in the distribution system? 6. Are the locations of the existing pipelines and valves known? 7. Is there is a hydraulic model of the distribution system? 8. Can the impacted area be isolated quickly in an interconnected system? 9. What can remote-sensing systems provide? 10. Where does the utility's responsibility to clean impacted infrastructure end? At the meter? 11. What is the contaminant's impact on residential infrastructure and water-using appliances? Copper pipes? Water heaters? Ice makers? 12. Whose responsibility is it to replace or fix impacted residential infrastructure and appliances?
Communications	1. How will communications be handled, including to internal personnel, to the public, to the business community and to elected and other government officials? 2. Which local government officials and offices need to be informed? 3. Who is responsible for internal, public and other communication activities during the recovery from this incident? 4. Who is responsible for communicating with the local critical customers (medical facilities, nursing homes, dialysis facilities, public school system) impacted by the event? 5. What state and local regulators (Division of Water, Emergency Management, Public Health, OSHA, and EPA) need to be informed? 6. What procedures have been previously developed for use during this type of emergency?

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Table 2. Continued.

General Area of Concern	Decision Points
	7. How would internal communication procedures change if normal communication links are disrupted? 8. How would it be determined if an advisory or public notification (such as boil water or do not use) needs to be issued for this incident? How would this occur without power and if normal communication media such as TV and radio outlets are unavailable? What alternative resources could be available to issue an advisory? 9. Where can you find information for release to the media regarding potential water contaminants? 10. How will the utility restore public confidence in the product provided? 11. How would the utility handle communications if the contamination incident was an accident vs. intentional? 12. How does a utility discern between an intentional and accidental contamination event?
Alternative Water Sources	1. Does the impacted utility have the capacity to supply potable water after the contamination event? If not, what are the alternative sources? 2. How will the alternative water sources be provided during long-term outages? 3. Does the utility have recommended delivery methods? Central distribution location? Temporary lines? 4. Who will pay for providing alternative water sources during long-term outages? Does this change if the contamination event was intentional? 5. How will the impacted utility recoup the associated costs? 6. How will critical care customers be supplied during long-term outages? 7. At what point can treatment facilities be established? 8. How will fire protection services be addressed in the contaminated area?
Coordination	1. What agencies or groups will the utility coordinate with concerning recovery and remediation? 2. What are the expectations for their support? 3. What specific coordination procedures have been developed to ensure successful coordination?
Business Continuity	1. During emergency operations including recovery and remediation, what outside contract services are available to provide services? 2. What priority will your contractors give you if other business and city operations are competing for the same equipment or services? 3. Who is responsible for covering the cost of impacted equipment (ice makers, laboratory equipment and manufacturing equipment)? 4. How does the utility assist small businesses?

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Table 2. Continued.

General Area of Concern	Decision Points
Logistics	1. What procedures have been developed to address logistical support (e.g., food, shelter and equipment for responders) during this incident? 2. What procedures and/or provisions are in place to support personnel with special needs (e.g., lost or damaged personal property, injured or killed family/friends and psychological impact from devastation) due to the incident? 3. If service is out for a prolonged period, how is alternative water going to be provided to impacted customers?
Local and State Coordination	1. How do current financial systems that track reimbursable expenses coordinate with local and state requirements?
Federal Coordination	1. What type of federal support do you expect to receive related to your long-term recovery operations? 2. Many types of federal aid are tied to restoring infrastructure to pre-event status – what are your options regarding incorporating enhancements or planned improvements as part of this restoration? 3. If the conditions in this scenario were to escalate and federal assistance was needed, what are the expectations for support and which agency would be contacted? Who will coordinate this effort at your utility?
Mutual Aid/Assistance (MAA)	1. If your utility does not have enough personnel during the incident, what other options are available and have arrangements been made in advance? 2. How are you going to manage the demands for long-term recovery, and should these needs be addressed in your MAA agreement?
Law Enforcement	1. What inspection or surveillance programs are in place to detect any physical security breaches in utility appurtenances, such as water storage facilities and the distribution system? Does your utility have a "neighborhood watch" or "water watchers" program in place within the served community?
Finance and Administration	1. What procedures have been developed to address incident-related expenses? 2. How are financial and other incident records maintained? 3. How will the lost revenue of impacted business be covered? What about the cost of lost products (food spoilage, contaminated products)? 4. Once a recovery plan is established, what is the financial impact on customers and the utility? 5. Will the utility's actions or inactions lead to legal liability?

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Table 3. Anywheretown example data inputs into Water Expert.

Water System	Anywheretown	
Location	Interstate	
	Contaminant Information	Network Information
Contaminant	Benzene	
Concentration	0.8	
Concentration Units	$mg\,L^{-1}$	
Date and Time	14 Feb 2014 10:00 LT	
Material		Polyethylene

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Table 4. Benzene contamination alert.

Alert Type	Action Needed
Public Health	Benzene concentration is sufficiently high to cause a public health concern. Please notify your consumers and you public health agency. Potential health impacts include – Anemia; decrease in blood platelets; increased risk of cancer

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Table 5. Benzene exceedence alert.

Species	Concentration	Trigger	Limit
Benzene	$0.8\,mg\,L^{-1}$	MCLG	$0\,mg\,L^{-1}$
Benzene	$0.8\,mg\,L^{-1}$	MCL	$0.005\,mg\,L^{-1}$

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Table 6. Benzene contaminant-material interactions.

Species	Material	Interaction
Hydrocarbon	Polyethylene (PE)	Prolonged exposure to hydrocarbons causes PE to degrade

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Table 7. Benzene treatment options based on USEPA (2004c).

Treatment Technology	Effectiveness Level
Advanced Oxidation Process	Most Effective
Activated Carbon	Most Effective
Air Stripping	Most Effective
Chlorine Dioxide	Less Effective
Chlorination	Less Effective
Ozonation	Less Effective
Ultraviolet (UV) Disinfection	Less Effective
Microfiltration, Ultrafiltration	Not Effective
Reverse Osmosis (RO) and Nanofiltration (NF)	Not Effective
Coagulation/Filtration	Not Effective
Ion Exchange	Not Effective
Activated Alumina (AA)	Insufficient Data
Chloramination	Insufficient Data
Direct Filtration	Insufficient Data

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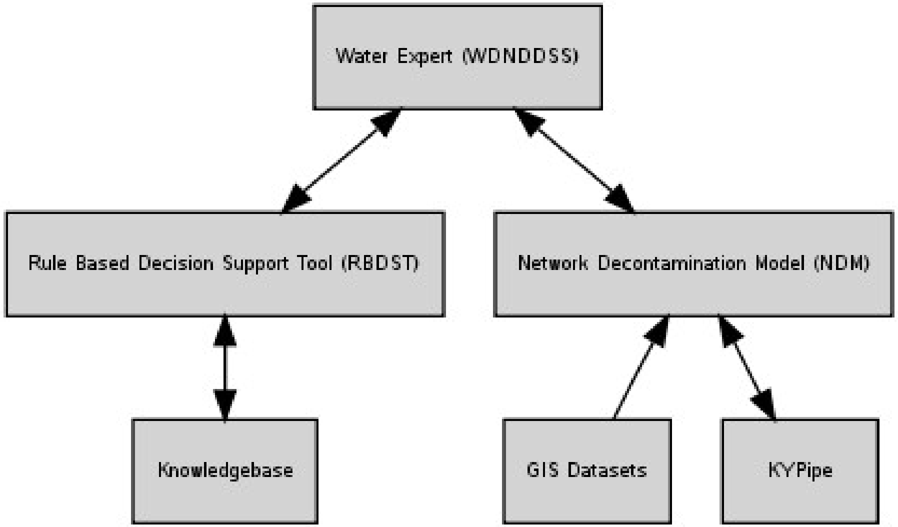

Figure 1. Flow diagram of the Water Distribution Network Decontamination Decision Support System (WDNDDSS), or *Water Expert*.

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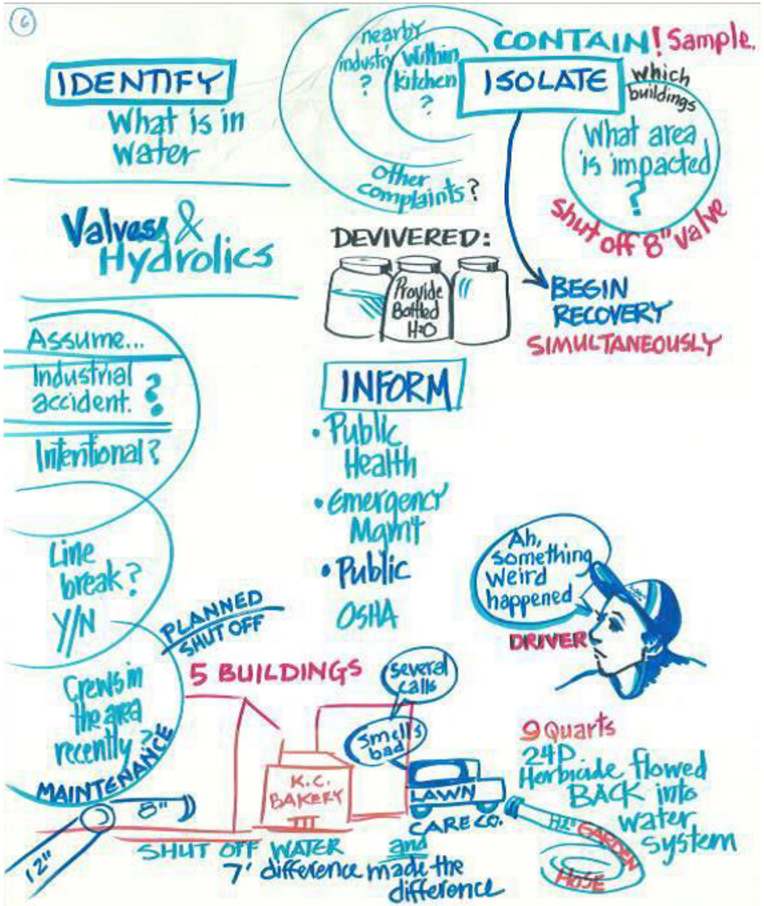

Figure 2. Mind map of hypothetical contamination scenario in which tabletop exercise participants determined key events and participant questions.

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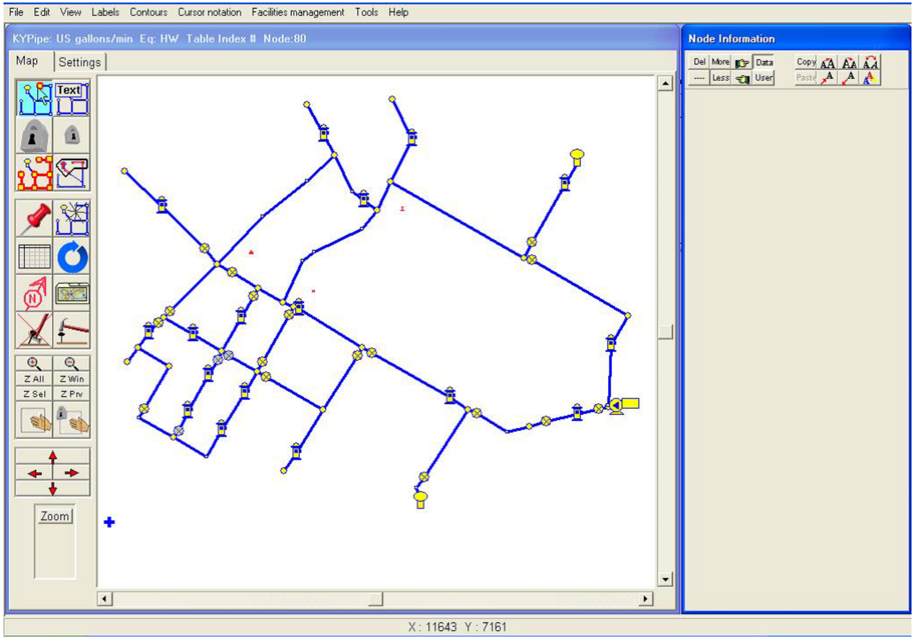

Figure 3. Example Network in the Network Decontamination Model. The NDM is an extension to KYPipe, a commercially available, hydraulic modelling software.

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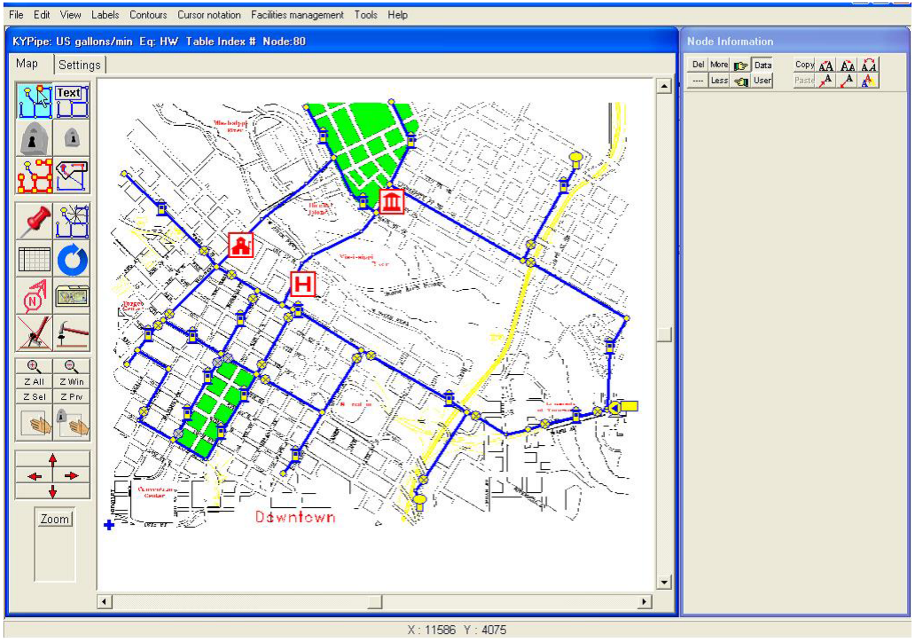

Figure 4. Network Decontamination Model with additional icons depicting the location of critical users and a backdrop map.

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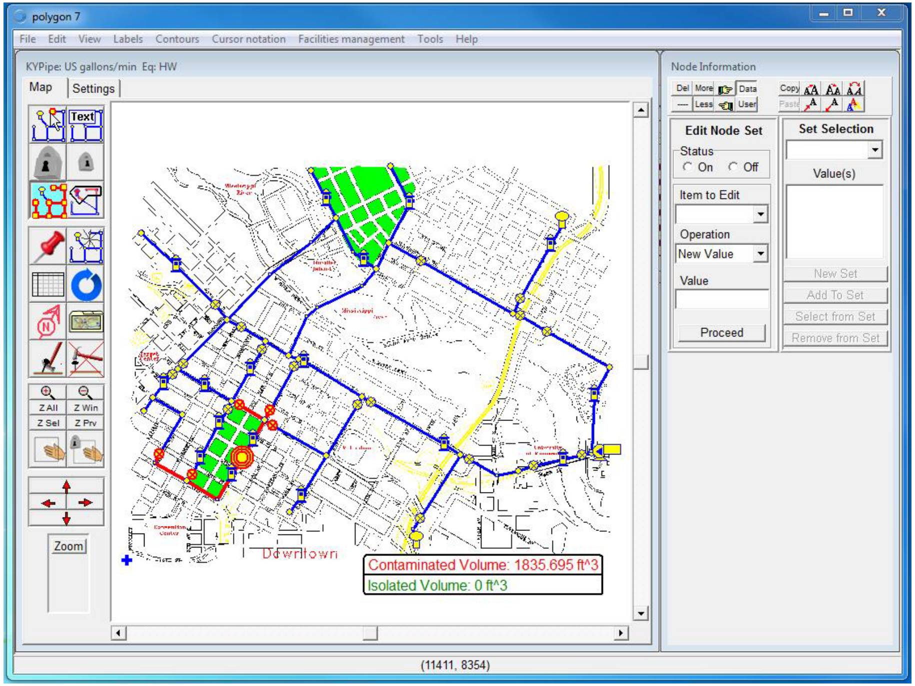

Figure 5. Example contamination event within the Network Decontamination Model

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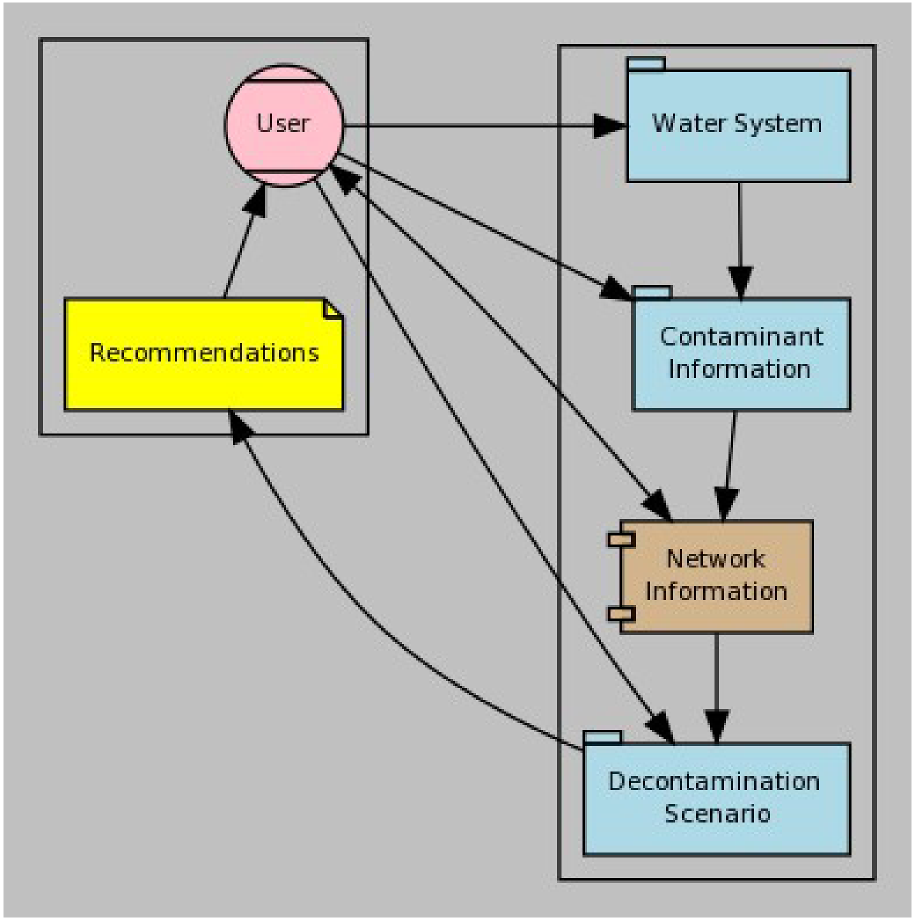

Figure 6. *Water Expert* system flowchart.

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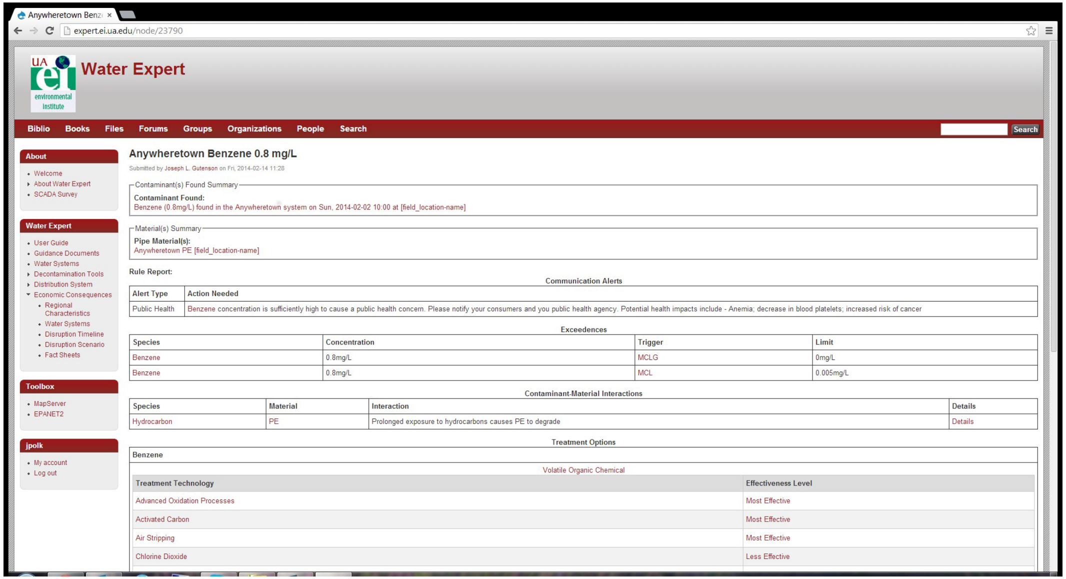

Figure 7. Example recommendation page generated by *Water Expert.*

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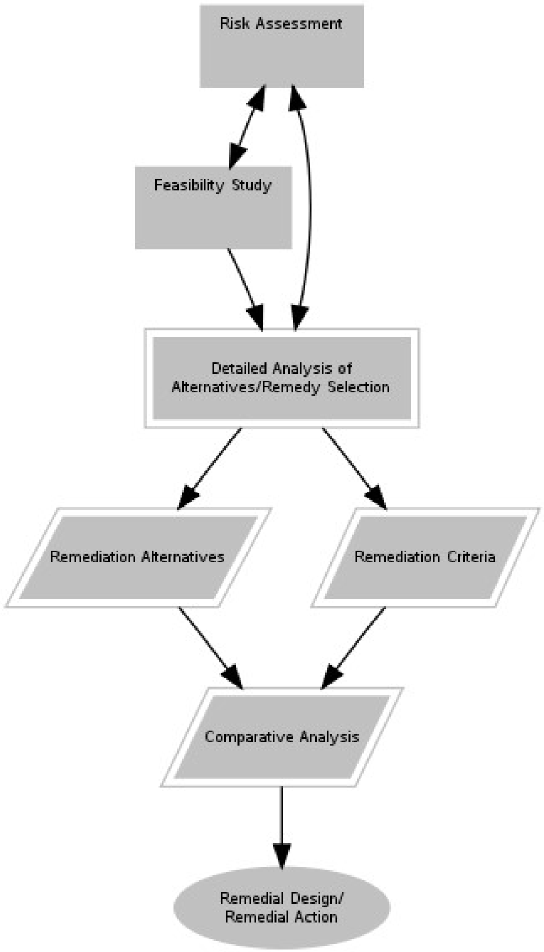

Figure 8. Interactive Flowcharts used to navigate the Guidance Documents. This particular example is based on content derived from USEPA (2004c).

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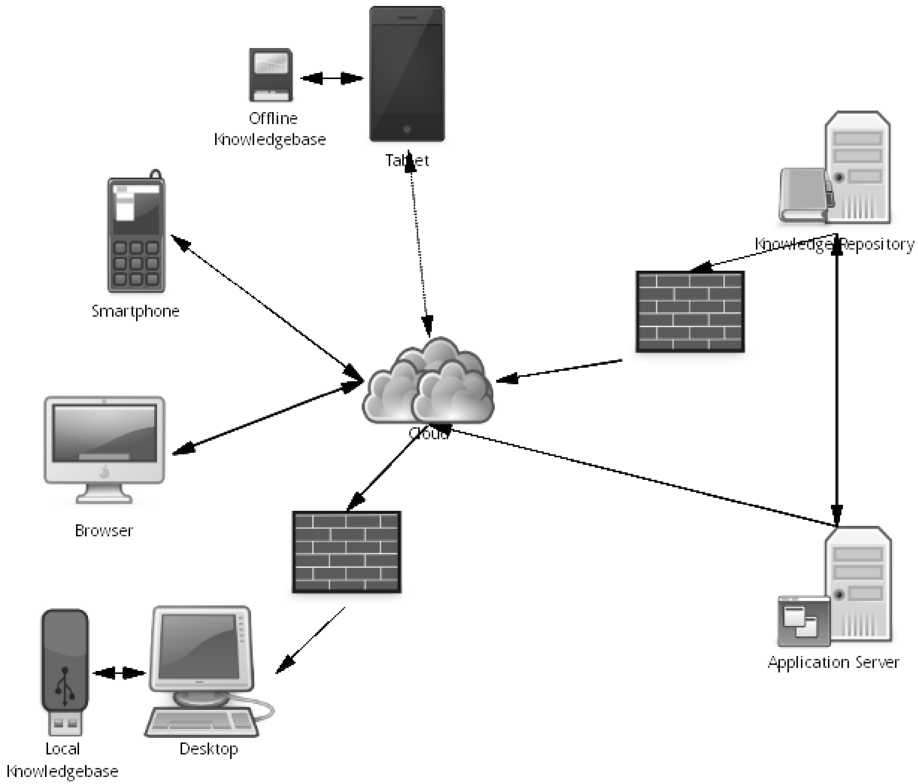

Figure 9. Future cloud deployed environment of Water Expert. It is envisioned that this environment will exist as a local, enterprise level system for individual utilities.

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