A System-Based Analysis and Approach for Water-Linked Health and Wellness in Low-Resource Setting

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ABSTRACT

Water is one of the valuable resources for human kind. The present status and future demand for water resources warrant a system-based multidisciplinary investigation of water-linked health and wellness issues. This paper presents a system-based analysis of these issues. In addition, a new approach incorporating three paradigms (prevention, detection, and management) to attain sustainable solutions using technological innovation in synchronization with socioeconomical issues has been proposed. A case study for arsenic in water in eastern India is also presented.

Keywords: water quality, health, wellness, disease, sensor, prevention, detection, management, sustainability.

1. INTRODUCTION

Water is a critical resource for any society. Both the quantity and quality (contamination) of water have significance for human health and wellness. Infectious disease can be fatal for children, women, and elderly people. According to a report (POUZN Project, 2007), lack of proper sanitation, water supply, and hygiene are associated with diarrhea (estimated 4 billion cases), waterborne diseases, and deaths of mostly young children in developing countries. Health consequences related to water, sanitation, and hygiene accounts for an estimated 4 billion cases of diarrhea and other waterborne infectious disease – mostly in developing countries (POUZN Project, 2007). Major contributors to these overall water-related health and wellness issues are pathogens, heavy metals (i.e., fluoride, arsenic, and mercury), chemicals/pollutants, and toxins. Consumable food products in contact with contaminated water pose additional threats in the form of water- and vector-borne illness.

Water-related health and wellness issues, in general, are not just limited to developing countries and are indeed global issues. In India, the water-linked health and wellness issues are also equally critical. With a population of >1.2 billion, many factors (i.e., irregular monsoon, climate change, lack of water supply and management infrastructure, water pollution and contamination, and rapid urbanization) contribute to a variety of water-linked health issues (Bhadekar, Pote, Tale, & Niricha, 2011; Mehta, 2012). Lack of sufficient and reliable water supply forces people to use nonhygienic water (from other sources) for nondrinking purposes, and this practice also causes health problems. Water pollution with pesticide, heavy metal, and pathogenic bacteria is also a growing problem (Bhadekar et al., 2011; Mehta, 2012) and is linked to diseases like cancer. For example, >21% of transmissible diseases in India are related to unsafe water (Mehta, 2012). According to a report (UNICEF, FAO, & SaciWATERs, 2013), 70% of surface water and a growing percentage of ground water are being contaminated by biological, chemical, organic, inorganic, and toxic pollutants. Similarly, water contaminated with arsenic (inorganic form) can cause multitude of diseases ranging from cancer, heart problems, to hepatic, renal, skin, and gastrointestinal problems (Elangovan & Chalakh, 2006).

Water-linked health and wellness issues are complex. They are connected with multiple cause and effect pathways. Many of the pollutants coexist in a given time. Thus, it is critical to address these issues from a system’s perspective for a single pollutant or a combination of pollutants.

2. OBJECTIVES

The objectives of this paper are to: (1) analyze the water-linked health and wellness issues from a system’s perspective, (2) provide a new framework for developing innovative solution for these issues, and (3) use this framework for preliminary analysis of arsenic contamination of water in eastern region of India.

3. A SYSTEM-BASED ANALYSIS

Water consumed at the household level can be grouped into two categories: water for drinking purposes and water for nondrinking purposes. Typically, in developed countries, water comes from the same sources for both drinking- and other nondrinking-related applications. However, in many low-resource settings, water from drinking and nondrinking applications could come from different sources – sometimes from more than two sources.
Figure 1 depicts an overview of the value chain of water consumption at the household level in low-resource setting. As the figure entails, path 1 (Figure 1) represents the conventional process in which water is treated and distributed for consumption at the user (household) level. In recent years, the awareness of using clean water for drinking purposes has created new industries that treat and market drinking water in a variety of portable containers (disposable bottles) (path 2 – Figure 1). The increased awareness of using purified or clean water has also created new industries in developing and selling commercial water filtration units (path 3, Figure 1). These units are mostly being used at the individual household level. However, these types of portable water filtration units might not be found in low-resource setting due to lack of affordability. Ground water is also used as source of water for drinking purposes. As shown in the figure (Figure 1, paths 4 and 5), it is consumed with full or partial treatment or without any treatment. In many cases, ground water is used as additional source of water in case of emergency or to augment the conventional water supply. In these cases, ground water is used for nondrinking applications.

The major forms of water contaminations are due to (a) heavy metal, (b) pesticide, (c) pathogens (bacteria), (d) toxins, and (e) others (oil, pharmaceuticals). Pathogenic contaminations pose immediate health threats causing infectious diseases (waterborne) that can be linked to illness or death. Other contaminants also pose serious health threats, but they are observed in a short- or long-term basis. Nevertheless, all these contaminants are linked with undesirable health and wellness.

Sometimes, the drinking water might be contaminated, and the status of contamination might not be known to the users. When access to drinking water (uncontaminated water) is limited, the users at the household level rely on surface water for other nondrinking applications (e.g., cleaning clothes and utensils and taking bath). If the access to drinking water is nonexistent, users rely on other forms of water sources (lake, pond, and ground water) for drinking and nondrinking applications. This water might be contaminated or might not have been treated before consumption. Many times, it is not known if the source of water is contaminated or not. A variety of local practices and beliefs are also used to assess the quality of water. For example, if the water looks clear visually, then it is acceptable for consumption. Similarly, the water from a well or a ground water source is acceptable for drinking purposes. Such beliefs are related to local culture or practices in a specific location. Nevertheless, water from the open surface or ground water sources might be contaminated with a variety of contaminants (including pathogens) threatening human health and wellness.

Multiple pathways of contamination exist for water resource systems. Surface water resources (lake, river, and ponds) and ground water can be contaminated by a variety of manmade practices. A few of them include
disposal of a variety of wastes (household, industrial, human, animal, and medical wastes) into the water system. In many regions, it is an acceptable social practice to use the same waterbody for both human and animal uses (e.g., cleaning, washing, and taking bath) and to use the same water for other nondrinking purposes. In many areas, open defecation (human and animal) is still prevailing. Runoff from these open defecation areas contaminates waterbodies (wells, ponds, lakes, and ground water). Runoff, flooding, and leaching from contaminated soil and water (with pesticide, waste, pathogen, and toxin) can also crosscontaminate other waterbodies. Specific geological makeup can also cause contamination in waterbodies.

Thus, it is important to analyze this water contamination issue from a system’s perspective and assess the critical points in the value chain along with the details of the contamination (type and level of contamination).

4. A MULTIDIMENSIONAL APPROACH – SUSTAINABLE SOLUTION WITH APPROPRIATE TECHNOLOGICAL DEVELOPMENT AND INNOVATION

We propose a holistic or system-based framework to address a given social issue like water-linked health and wellness. We call this approach “sustainable solution with appropriate technological development and innovation (SWADIN).” This approach is designed to create a sustainable solution for a given problem to be used in low-resource setting. To attain sustainable solution, this approach focuses on developing innovating technologies that are appropriate for a given location. Thus, the developed technology can use locally available materials and resources to enhance its sustainability and cost effectiveness. This strategy has advantages against the conventional approach, wherein technological solution is transferred or transplanted from the developed countries to be used in low-resource setting (developing countries). In this later approach (conventional), the solution might not be sustainable due to the lack of technical know-how or required infrastructure to support the developed solution framework at the place of use (in low-resource setting).

In addition, our proposed approach has the following guiding principles:

1. Understand the problem from the end user or stakeholder’s perspective and identify the needs.
2. Involve the stakeholders (the victim of the problem) with the solution-development process from day one so that they become the advocate of the developed solution.

It is also important to know how the stakeholders (associated with the problem) have been dealing with the problem at the time of initial interaction. Many times, the stakeholders might have developed their methods of dealing with the problem. Even if their adopted methods might not be the targeted solution, those can provide valuable insights toward the targeted solution.

3. Identify the economical, social, geographical, cultural (behavioral), market, and policy (legal and governmental) factors related to the issue (to be addressed). Use these factors as constraints or design factors (in addition to the technical design factors) to develop the solution (Figure 2).

4. Design solution from the user’s perspective that is synergetic of three paradigms – prevention, detection, and management – related to the given issue. Figure 2 illustrates the three interactive paradigms – prevention, detection, and management – as the three vertices of a triangle. For a given water contaminant (pollutant) in the water value chain, prevention paradigm focuses on remediation or intervention activities to reduce or eliminate the contaminant from the water before it is consumed. Detection paradigm focuses on detection or sensor system that can detect or predict the magnitude of a contaminant at a given point in the value chain. Both the detection and prevention paradigms can work interactively for effective process management. The management paradigm includes the relevant activities or processes that are required for successful execution of the developed solution at the stakeholder’s level. Even though the three interactive paradigms are ideally suited for a specific sustainable solution development and management process, dual paradigm combinations (e.g., prevention management and detection management) can also be used for specific cases.

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5. A CASE STUDY – WATER AND ARSENIC PROBLEM IN EASTERN INDIA

Reports indicate that ~6 million people were affected by arsenic in West Bengal alone (Elangovan & Chalakh, 2006). In this paper, we conduct a system-based analysis of arsenic problem of water in the eastern part of India using our proposed three interactive paradigms – prevention, detection, and management.

5.1 Prevention paradigm

Review of literature indicates extensive efforts to remove arsenic from water in this region. Removal of arsenic comes under the “prevention” paradigm of our approach. Das et al. (n.d.) reported a simple device for the removal of arsenic from ground water. Though many research has been conducted for remedial aspect of arsenic from water. The investigators of this study developed a device using materials that are locally available or affordable for the stakeholders (local). For example, their system used earthen pot or plastic jar. Their patented design was inspired by the adopted practices of the affected villagers. This device could process 20 L of water – meeting the water consumption need of a four-member family. The device was effective (93–100%) for removing arsenic. This study further reinforces that transplanting a technology, successful in developed country, may not work in low-resource setting. This study also verified the importance of (a) engaging the stakeholders (the users of the intended technology or the victim of the problem) for the development of the solution and (b) considering the associated socioeconomical factors along with the stakeholder’s attitude, culture, and beliefs.

5.2 Detection paradigm

A field scale detection unit to determine the level of arsenic in drinking water is a necessity. Such a detection unit can be an integral part of arsenic management system. Similarly, detection unit can also work in synchronization with prevention (remedial) system for arsenic. Realizing the needs, many researchers have investigated on developing detectors or detection methods for determining arsenic content in water in both the laboratory and field conditions (de Mora et al., 2011; Niedzielski & Siepak, 2003). In this paper, we have identified selected prior work that has potential in terms of accuracy and portability for field scale applications. Colorimetric method has been used by many researchers (Lasko, Rose, Peoples, & Shirachi, 1979; Morita & Kaneko, 2006). Interferences with other metal ions or compounds (i.e., zinc, copper, and phosphorous) were a few reported challenges. Additional reported challenges included safety issues associated with the use of reagents (mercury) and acid (hydrochloric or sulfuric) for arsenic detection (Baghel, Singh, Pandey, & Shekar, 2007; Cherukuri & Anjanyulu, 2005). A few of these challenges have been addressed by other researchers. For example, Baghel et al. (2007) reported a rapid color-based arsenic detection method that used oxalic acid and magnesium turning along with gold chloride. They indicated detecting arsenic at 10 and 50 ppb in 1 and 10 min, respectively.

Recently, the colorimetry framework has been extended to integrate the advancements of nanotechnology and microtechnology for the detection of arsenic in water. Xia et al. (2012) used unmodified gold particle along with peptide (containing phytochelatin like). The obtained detection limit was 20 nM (lower than World Health Organization’s [WHO] recommended limit). In the same line, Kalluri et al. (2009) reported gold nanoparticle-based assay for arsenic detection in ground water using dynamic light scattering (DLS) particle method. Their reported sensitivity was three magnitude more than WHO’s recommended limit, and the detection time was 10 min. The authors reported the detection capability at parts per trillion (ppt) level. They also tested their system with water samples from different areas including Bangladesh, wherein arsenic problem in water is severe. This DLS-based method has potential advantage of being simple, fast, and sensitive.

Analysis of these detection methods for field scale deployment in low-resource settings: Here, the above-described (three) detection methods have been theoretically evaluated for their field scale deployment in low-resource setting. In each of these cases, technical feasibility has been demonstrated by the corresponding researchers. In this paper, we used additional parameters (i.e., economic, safety, and other feasibility factors) to assess the field scale deployment capability of the detection methods.

Method based on oxalic acid and gold chloride (Baghel et al., 2007) is rapid and has potential for field scale deployment. Our estimated cost of the system based on the cost of the used reagents is $1–3 and thus the system has potential for use in low-resource settings. With additional subsidy, it has potential for mass scale deployment. However, additional investigation is needed on how to properly handle the generated arsine gas (as a part of the intermediate reaction that reacts with gold chloride to produce visible color) to prevent additional safety hazard for the user.

The detection method (Xia et al., 2012) using gold nanoparticle has low detection limit and has high potential for near-field arsenic detection applications in low-resource setting. The cost of the required material
for detection (gold nanoparticle and peptide) will be an economical constraint for use in low-resource setting. In addition, the stability and life time of peptide in field condition (high temperature, lack of cold storage) need to be investigated. Similarly, the detection method using DLS (Kalluri et al., 2009) used gold nanoparticle conjugated with specific peptides or amino acid. Its excellent sensitivity makes it an appropriate device to be used in near-field laboratory setting. The cost for the gold nanoparticle and peptides will be additional economical constraint for low-resource setting. Similarly, the stability and life time of the peptide/ amino acid needs to be investigated. Moreover, the cost of the required instrument, DLS (DLS system) for this detection method will be an additional constraint in low-resource setting.

5.3 Management paradigm

As discussed earlier, management is critical for implementing a sustainable solution of a societal issue like water-linked health and wellness. This paradigm can work with both the detection and prevention (remediation) paradigms.

Thus, for addressing arsenic issue in water, an integrated systems’ approach is recommended. For example, the arsenic prevention work (Das et al., n.d.) further indicated how the stakeholder’s awareness and usage practices also played an important role in sustainability of the implemented solutions. When the filter system was clogged up with arsenic, the washed materials from the filter were disposed in soil, and cow-dung was added to the materials. It was not clear from the paper if the adopted process posed any additional long-term burden of arsenic in the environment. This is an example where a system-based approach in proper disposal of arsenic from the arsenic remedial system would be appropriate. Similarly, many times, the developed arsenic removal or filtration system is not integrated with arsenic detection system. However, incorporating a low cost field-scale detector with arsenic removal system will be more effective in monitoring, performance assessment, and management (replacement) of the arsenic remediation system.

Our initial analysis indicated that a system-based approach for addressing arsenic contamination in eastern India and other specific areas would be beneficial. Extensive researches have been conducted for arsenic contamination in water by different researchers around the world, and these researches can be grouped into one of our described paradigms – prevention, detection, and management. Thus, we justify the need of developing sustainable solutions for such problem (arsenic contamination in water) tailored to a specific region or area. This process could involve the adaption of the prior research and development or could involve development of new techniques via systematic research and development.

6. BEYOND ARSENIC IN WATER

Besides in drinking water, arsenic is also present in many other natural entities (Bencko & Slamova, 2007). It can enter human system via food chain (Bencko & Slamova, 2007). Arsenic in soil or in water can contaminate food products (for both animal and human). We call it “induced effect.” For example, arsenic in agricultural soil or arsenic-contaminated irrigation water can end up in rice or grain. Arsenic-contaminated irrigation water can be absorbed by rice straw, an important animal feed in India and other parts of the world. Subsequently, this can affect animal health and indirectly affect human health (via milk and meat) (Abedin, Cotter-Howells, & Meharg, 2002). Thus, management, detection, and/or prevention paradigm in this specific segment need to be addressed. It is also critical to address this issue.

Besides arsenic, other pollutants (heavy metals, microbial contaminants, toxins, and pesticide) found in waterbodies in India (UNICEF et al., 2013) are of concern to human health. Similar conditions are expected to be found in other countries in the world too. It is to be noted that many times these contaminants could coexist. Thus, besides adopting a systems’ approach in creating solution for these issues, it will be advantageous if the developed solution could be modular to address health and wellness issues related to multiple water contaminants.

7. SUMMARY AND FUTURE DIRECTION

It is timely to develop sustainable solutions for water-linked health and wellness issues – to be deployed in low-resource settings. The developed solution must be such that it is appropriate from technological, economic, social, and cultural perspectives. Thus, a new framework – SWADIN – has been proposed. We postulate that both a system-based approach with focus on technological innovation at multiple points (in the value chain of health and wellness issue) is necessary. We have developed and illustrated an interlinked synergetic paradigm – prevention, detection, and management – to address such societal issues. Based on a case study analysis of arsenic contamination in water in the eastern region of India, we further justified the need of adopting a system-based approach to address one or multiple water-linked health and wellness issues.

We need to devise innovative solutions that will be sustainable, equitable, and be accepted by the users in a given demographic. Advancements in sensor,
microelectromechanical system, and information technologies along with their miniaturization show tremendous potential for technological innovation. The rapid growth of cell phone (smart phone), portable computing, and associated information technology will also support the proposed activities. To augment the required technological innovation, it is important to create a common domain or platform – we call it “solution domain” – wherein all the stakeholders with crosscutting disciplines and expertise can work interactively. For example, our current team involves researchers and collaborators from multiple disciplines ranging from economics, communication, microbiology, social science, toxicology, civil engineering, electronics, sensor, water law and policy, medicine, and microbiology.

Our current and future work involves developing systems and processes that can operate within the framework of three interactive paradigms – prevention, detection, and management – to create solutions addressing water-linked health and wellness issues.

REFERENCES


Dr. Suranjan Panigrahi, a professor in the Department of Electrical and Computer Engineering Technology at Purdue University, West Lafayette, IN, USA, has 23 years of comprehensive experience in research, teaching, and extension. Dr. Panigrahi’s research focuses on the development of smart systems to prevent, detect, and manage critical (safety and wellness) issues in biological systems. He adopts a system-based approach to develop and integrate intelligent sensor techniques with advanced electromechanical and computer-based information and machine-learning technologies. He has crossdisciplinary training and expertise in engineering, biological systems, sensors, electronics, information technologies, and management (MBA). He has successfully innovated multiple technologies for agricultural/biological food applications. He is the lead inventor of three approved U.S. patents (related to field scale quality sensors). He is the author/coauthor of >150 technical papers, publications, and book chapters including patents and software. He was the founder/director of an interdisciplinary research center “Bio-Imaging and Sensing Center” at North Dakota State University for 9 years. He is passionate about creating disruptive innovation for critical societal issues. One of his recent research thrusts is to create innovative sustainable solutions for water- and food-linked health and wellness issues. He has mentored >24 graduate students and eight postdoctoral associates (visiting scholars). His past students are employed as either tenure track faculty members in several U.S. universities or are in key technical and management positions in private companies. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), American Society of Engineering Education (ASEE), American Society of Agricultural and Biological Engineers (ASABE), and Gamma Sigma Delta (honor society).