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A systems analysis of irrigation water quality in environmental assessments related to foodborne outbreaks

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Abstract

Irrigation water quality can affect food safety and health and has been identified as a possible source of pathogens in produce linked to disease outbreaks. Many irrigation water sources are subject to contamination from various sources in surrounding watersheds. A systems-based, watershed scale analysis is therefore necessary to comprehensively identify both sources of contamination and the conditions in the environment that facilitated or created that contamination, termed here ‘environmental antecedents’. Three nationwide disease outbreaks linked to produce in the United States (US) are used to illustrate this concept of a watershed scale assessment to investigate potential impacts of irrigation water quality on food safety.

Keywords

irrigation water quality; foodborne outbreak; systems analysis; environmental assessment; Water Safety Plan

1. Introduction

Epidemiological data indicate a significant number of foodborne illness outbreaks associated with the consumption of contaminated fresh produce. In the US during the period 1973 to 2006, 10,421 foodborne outbreaks were reported, of which 502 (4.8%) outbreaks, 18,242 (6.5%) illnesses and 15 (4.0%) deaths were associated with leafy greens (Herman et al., 2008). There has been significant food safety research focused on risks in harvesting, packaging, processing and handling fresh produce, emphasizing the control or elimination of microbial contamination at these points. This reflects the concept of the Hazard Analysis Critical Control Points (HACCP) approach, which seeks to assure food safety from production to consumption (NACMCF, 1997). However, this approach has not always consistently included pre-harvest factors that may also affect food safety. One example of such a pre-harvest factor is the quality of irrigation water, which has been identified as a possible source of contamination of fresh produce. Bos et al. (2010) summarize documented information on illnesses and outbreaks related to consumption of uncooked vegetables irrigated with wastewater. In addition, irrigation water has been identified as a potential source of contamination in several disease outbreaks in the US involving leafy green

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produce irrigated with environmental water (not wastewater). These events included an Escherichia coli O157:H7 outbreak associated with fresh bagged spinach in 2006 (Gelting et al., 2011), and a separate outbreak in 2006 involving *E. coli* O157:H7 associated with shredded iceberg lettuce served in chain restaurants (CalFERT, 2008), both of which were traced back to farms in California. Another outbreak in 2010 involved *E. coli* O145 associated with romaine lettuce traced back to a farm in Arizona (Crawford et al., 2010). All of these outbreaks caused multiple illnesses across various states, as well as five deaths in the case of the 2006 outbreak associated with spinach. While this paper focuses on the potential role of contaminated irrigation water in these outbreaks, multiple other factors were involved or potentially contributed to the outbreaks and the quality of irrigation water was only one potential determinant of the outcomes.

In order to investigate the possible role of irrigation water in contamination of leafy green produce in these outbreaks, in-depth field environmental evaluations were included in the investigations of each outbreak. We term these evaluations ‘environmental assessments’ in keeping with terminology currently used in the US for outbreak-related environmental investigations. (Note that environmental assessment as used here is distinct from the process of environmental impact assessment used to determine possible environmental impacts from proposed projects.) This paper focuses on the portion of the environmental assessments that focused on irrigation water, but the concepts of environmental assessment can also be applied to other potential sources of contamination. Environmental assessments utilize a systems-based approach, defined as “the process of studying or understanding the entirety of a problem and the underlying interactions and interrelations among all the elements constituting that problem” (Gelting et al., 2005). These assessments therefore took a broad approach to identifying potential sources of contamination of irrigation water, looking at factors both on the farms themselves where the produce originated, as well as in surrounding watersheds. Such an approach can help to identify not only possible sources of contamination, but also the conditions in the environment that facilitated or created that contamination. These conditions are termed environmental antecedents here, and are the circumstances that allow contributing factors that can affect health, such as contaminated irrigation water, to occur (Gelting et al., 2005). The term environmental antecedent as used here could be thought of as a specific outbreak-related form of an environmental determinant of health in terminology used by others, although environmental determinants of health are a much broader concept. Identifying environmental antecedents to outbreaks is important because it can, in turn, help to identify mitigation strategies to help prevent future outbreaks. A systems-based environmental assessment also includes a time element, to ascertain if environmental antecedents or contributing factors vary over time, which may help to identify or explain contamination events that are episodic and not continuous.

Because environmental assessments involve a broad and comprehensive strategy for identifying environmental antecedents and contributing factors, the process can incorporate analyses at varying scales, from entire watersheds to on-farm conditions. Elements anywhere along this continuum from watershed to farm may influence contamination, and so need to be included. The three outbreaks discussed here provide examples of conditions along this continuum that may influence irrigation water quality. In the 2010 outbreak in Arizona, the environmental assessment revealed that elements in the watershed beyond the farm where the lettuce originated might have been potential sources of contamination of irrigation water. The environmental assessment for the spinach outbreak in 2006 uncovered elements both in the watershed and on the farm that could potentially have contributed to irrigation water contamination. Lastly, irrigation water management practices on the farm itself appeared to be the most likely source of contamination in the 2006 lettuce outbreak. The environmental assessments for each of these outbreaks are discussed further below.

2. Methods

Standardized procedures for environmental assessments are still being developed, but assessments of potential sources of contamination of irrigation water should include analysis of watershed characteristics, irrigation practices, and surface and ground water hydrology. Specific activities can include the following:

- Identifying surrounding watersheds that may influence conditions on farms
- Characterizing surface and ground water hydrology in watersheds before and during the outbreak
- Identifying potential sources of contamination in the watershed
- Identifying potential routes for contamination to reach irrigation water
- Identifying and characterizing sources of irrigation water on farms
- Helping identify critical areas for prioritizing water quality sampling
- Identifying seasonal or other changes in surface water and ground water.

Because an environmental assessment includes a broad set of activities, expertise from multiple disciplines such as hydrology, water quality, microbiology and food safety is typically required. Drawing these disciplines together may also require personnel from various organizations involved in environmental health, irrigation water management, watershed management, or other areas.

Data sources for environmental assessments can be quite diverse and may be dependent on the specific conditions or situation of a particular outbreak. Nonetheless, the activities listed above that are included in the environmental assessment should drive the types of data that need to be collected. Examples of data sources used in past assessments involving potentially contaminated irrigation water have included:

- Flow records for rivers and streams in watersheds
- Precipitation records on farms and in watersheds
- Drillers' logs for wells on and near farms identified by traceback investigations
- Locations of irrigation wells relative to contamination sources and surface waters
- Records of depth to ground water in monitoring wells over time
- Water quality analyses for both ground water wells and surface waters
- Data on location and timing of percolation from surface waters into ground water

- Records of direct use of surface water for irrigation on farms
- Water quality sampling for specific pathogens involved in outbreaks and water quality indicators

3. Analysis

Investigations undertaken in response to the outbreaks mentioned above provide examples of systems-based environmental assessments. These outbreak investigations all included in-depth environmental assessments by multidisciplinary teams designed to uncover potential environmental antecedents and contributing factors from various environmental sources. Various organizations were involved in these assessments, including the US Food and Drug Administration (FDA), the California Department of Public Health, Food and Drug Branch (CADPH FDB), the Arizona Departments of Health Services, Agriculture, Water Resources, and Environmental Quality, as well as irrigation and water management agencies in both states. The information presented in this paper focuses on that portion of the environmental assessments dealing with potential contamination of irrigation water, in which the authors participated at the invitation of these partners.

3.1. 2010 outbreak involving romaine lettuce

In the first example, 33 cases of bloody diarrhoea were reported in five states. Laboratory analysis identified matching strains of O145 Shiga toxin-producing *E. coli* (STEC) as the infectious agent. Epidemiologic investigations revealed that consumption of shredded romaine lettuce was associated with these illnesses. A traceback investigation by the FDA identified a single farm in Arizona as the source of the romaine lettuce.

An initial on-farm investigation by the FDA did not find any farm-specific contamination indicators. The scope of the investigation was therefore widened to include a watershed-based environmental assessment. Initial investigation showed that the lettuce fields were solely irrigated by surface water from an open-channel irrigation canal network. Analysis of precipitation data showed higher than average cumulative precipitation in the surrounding Gila River watershed late in the growing season in the month of January. Evidence suggested that the high volume of precipitation and the rainfall intensity in January created higher runoff potential that might have created a pathway for land-based microbial contaminants to contaminate the lettuce fields directly or by microbial loading into the irrigation canal network and subsequent use of water from there for irrigation. In light of this initial assessment, the focus of the environmental assessment shifted to contamination sources in the watershed and hydrologic processes as pathways of contamination of irrigation water that could have potentially contaminated the lettuce crops.

A reconnaissance survey of the Lower Gila watershed was conducted as part of the environmental assessment to identify contamination sources and potential pathways to the lettuce fields, including potential connection to the canal network. A concentrated animal feeding operation and dairy farm were identified in the valley but the canal laterals carrying water to the lettuce fields were upstream of these facilities and no hydrologic pathway could be established between them and the lettuce fields. Consequently, these facilities did not present a contamination risk to the lettuce crops.

A housing subdivision located on a mesa near the main irrigation canal carrying irrigation water to the lettuce fields was also identified as a potential source of contamination. However, the subdivision employed package treatment systems to treat its wastewater, and the treated wastewater effluent was used for landscaping purposes in an artificial pond that did not have any signs of overflow or leakage to the canal channel. This was further confirmed by negative samples collected from different locations on the subdivision. Therefore, the subdivision was ruled out as a potential source of contamination for this outbreak.

A recreational vehicle (RV) park located on a mesa adjacent to the lateral canal carrying water to the lettuce fields was also identified as a potential source of contamination. Inspection of the RV park surroundings, an interview with the manager and review of documentation revealed several potential environmental antecedents that may have contributed to contamination of irrigation water. During an interview with the manager, it was ascertained that the park depended on on-site wastewater treatment systems to treat its sewage using multiple septic systems with multiple drainage fields. Review of the documentation and engineering plans for the treatment systems showed the location of drainage fields in the vicinity of the lateral canal that serviced the lettuce fields. A review of soil maps for the RV park site also showed that the soil type was not suitable for septic absorption fields due to poor infiltration capacity. Moist soil along the side of the property adjacent to the canal indicated drainage toward the canal. At the time of the inspection, no surface source for the soil moisture was observed, indicating that the moisture was from a subterranean source and thus possibly from the RV park septic systems. Soil samples collected from these moist areas tested negative for STEC. However, drag swabs and mud collected from the lateral irrigation canal in the vicinity of the RV park tested positive for STEC but were not a match for the outbreak strain. These positive samples suggested potential surface runoff as well as subterranean drainage pathways for wastewater contamination to reach the canal system. Furthermore, available information suggested that the runoff pathway was possibly exacerbated by heavy precipitation earlier in the growing season. Although no definitive confirming evidence was found, the available information indicated the RV park as a potential source of the STEC detected in the drag swabs and mud collected from the adjacent lateral canal. This evidence suggested that the RV park potentially could have been the source of the outbreak contamination, however, no definitive confirmatory evidence was found.

3.2. 2006 outbreak involving spinach

In the second example, a 2006 outbreak involving *E. coli* O157:H7 that caused over 200 illnesses and five deaths in 26 states was linked to fresh bagged spinach. Traceback investigations by the FDA and CADPH FDB identified a single farm in California as the source of the spinach. An environmental assessment was undertaken on and around that farm, and included a component focused on irrigation water. This component included a watershed scale assessment of the farm's surroundings to identify factors related to irrigation water that may have contributed to contamination of the spinach. The watershed assessment identified several environmental antecedents both in the watershed and on the farm itself that could have contributed to contamination of irrigation water.

Extensive environmental sampling in the vicinity of the farm found positive *E. coli* O157:H7 samples that matched the outbreak strain in water from the river flowing through the farm and in cattle faeces in the river (Jay et al., 2007). The source of irrigation water on the farm was ground water pumped from wells. However, the environmental assessment revealed a potential connection between ground water pumped from these wells and surface water in the river.

Because of heavy demands for irrigation water during the growing season in this part of California, ground water was recharged through releases from upstream reservoirs into streams. Runoff is stored in reservoirs during the winter rainy season, and then released during the dry summer season to percolate through streambeds and recharge aquifers so they can continue to be used for irrigation. The river flowing through the farm in question was one of the watercourses into which stored water was released to recharge aquifers. On the farm, a well used for monitoring the depth of ground water showed that ground water was above the level of the river early in the growing season, so recharge into the aquifer underlying the farm was not taking place then. Between July and October of 2006, the elevation of ground water on the farm dropped to below the level of the river bed, so that recharge from the river to ground water would have taken place on the farm during that time. The spinach crop that was linked to the outbreak was also in the field during this period.

The hydraulic connection established between surface water and ground water during recharge could potentially contaminate ground water used for irrigation if the ground water was under the direct influence of surface water at the time it was pumped. This is dependent on several factors, including the subsurface environment, time of travel in the subsurface, and depth. Although ground water is generally considered a hostile environment for bacteria, some studies have shown that pathogens can persist in ground water (Yates and Yates, 1988). Well logs for wells on the farm showed that the irrigation wells penetrated variable sediments, including coarse grained layers where survival and transport of pathogens would be enhanced (Yates and Yates, 1988). High rates of pumping of agricultural wells on the farm (up to 11,000 litres per minute for 8 hours per day) could also contribute to rapid transport in the subsurface.

Based on the available information, the environmental assessment concluded that surface water-ground water interaction resulting in potential contamination of ground water used for irrigation was the most likely water-related environmental antecedent involved in this outbreak. However, the environmental assessment was not able to produce definitive evidence that this occurred. Other factors, such as contamination by wildlife that had ready access to the spinach field, were also possible, and samples of faeces taken from wild pigs trapped on the farm showed an *E. coli* O157:H7 strain matching that of the outbreak.

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3.3. 2006 outbreak involving iceberg lettuce

The final example of a systems-based environmental assessment comes from a 2006 outbreak involving iceberg lettuce served in chain restaurants that was contaminated with *E. coli* O157:H7. This outbreak caused 77 illnesses in two US states. A traceback investigation by FDA and the states revealed that the lettuce originated from various farms in several regions of California. Sampling by the California Food Emergency Response Team (CalFERT) determined that a genetic match between environmental samples (including water and soil) from a single farm and the outbreak strain existed. Further investigation, including an environmental assessment was then undertaken at that farm.

The environmental assessment determined that the environmental antecedents that potentially could have contributed to the contamination of irrigation water were all on the farm or in the immediate vicinity. The farm was located adjacent to two large dairy farms, and the assessment found that the farm's irrigation systems and the dairies' wastewater effluent systems were interconnected. Three sources of irrigation water were used on the farm: ground water pumped from on-site wells, surface water delivered to the farm through a pipe network by a local water management agency, and effluent from wastewater lagoons on the dairy farms. Water from these three sources was distributed on the farm through a complex piping network. The wastewater effluent was blended with water from the other sources and used only to irrigate animal feed crops. Crops intended for human consumption were irrigated with water from wells or water delivered by the local water management agency. However, water management practices on the farm, including control of the wastewater blending process, appeared to create potential for cross-contamination. Inadequate backflow prevention between piping networks used to convey blended wastewater and the other two water sources was present, and had been noted in inspection reports by regulators. In addition, the process for blending wastewater effluent was controlled using valves not designed for this purpose. This could lead to wear or failure, resulting in the valves not completely closing and potentially allowing cross-contamination between the wastewater effluent and water from the other sources.

The hydraulics of the complex piping network on the farm also appeared to contribute to potential for cross-contamination. Pressure in the delivery system managed by the local water management agency varied according to demand, with lower pressures during periods of lower demand. There were direct connections in several places between parts of the on-farm pipe network that carried wastewater effluent and water from the other sources. If higher pressures in the on-farm system from ground water pumping coincided with low pressures in the water management agency system, water from the on-farm system could potentially be forced back into the water management agency system, contaminating water in the latter system. Other factors could contribute to this, including the inadequate backflow prevention in place between the two systems. In addition, according to available records from the water management agency, there were several days of low or no demand (which may have corresponded to lower pressures) in the water management agency system during the time that the lettuce crop associated with the outbreak was in the field.

The environmental assessment revealed one further potential environmental antecedent that could potentially have affected the quality of irrigation water used on the farm: the lagoons used on the dairies to collect, treat and store dairy wastewater. Studies have highlighted risks of ground water contamination from dairy lagoons (Parker et al., 1999). Regulatory inspections of the dairies had noted the possibility of ground water contamination from the dairy lagoons, especially given the shallow depth to ground water in the area, ranging from 8 to 17 metres. Because of the proximity of the farm to the dairy lagoons, ground water pumped from wells on the farm and used for irrigation could potentially be contaminated by the lagoons.

In this case, the irrigation system on the farm had expanded and changed over time to meet various needs and to take advantage of changing conditions. For example, when the dairy wastewater effluent became available, it was treated as a resource in this arid area. Nonetheless, the changes implemented in the irrigation network were never accompanied by an overall systems-based analysis of the potential for contamination of irrigation water that they potentially created. Despite the issues identified with the irrigation system on this farm, the environmental assessment was unable to provide conclusive evidence of how irrigation water used on the lettuce crop might have become contaminated.

4. Conclusions and Recommendations

The type of in-depth environmental assessments at a watershed scale discussed above has not always been incorporated into outbreak investigations. However, these assessments are becoming more common, and are starting to be incorporated into outbreak investigations involving fresh produce. This is important, as more examples and experience will help to improve the process. As mentioned above, none of the environmental assessments discussed in this paper provided conclusive evidence of how irrigation water could have been contaminated with pathogens linked to specific foodborne outbreaks involving fresh produce. Nonetheless, each one helped to improve the process of environmental assessment and to highlight elements that should be considered for future assessments. As more environmental assessments are performed, more standardized procedures will be developed and improved, improving the process. Relationships between organizations possessing appropriate expertise will also be built, enhancing collaboration and facilitating future environmental assessments. Sources of data for environmental assessments can be quite diverse, and more experience with these assessments will also help to identify and standardize the type of data that need to be collected. In addition, more personnel with the appropriate background and skills to conduct environmental assessments are needed, and additional assessments will help to build a workforce with this experience. More experience with environmental assessments will also help facilitate the development of training materials for workforce development in this area. Timely implementation of environmental assessments is also critical, as conditions on farms and within watersheds can change rapidly, and it is important to assess a situation as close to that of the outbreak as possible.

As environmental assessments become more widespread, all of these factors limiting their implementation and effectiveness should improve. The results from improved environmental assessments will also help to develop more effective strategies to prevent outbreaks. Management of irrigation water may also benefit from a more formalized preventive approach similar to the World Health Organization’s (WHO) Water Safety Plan (WSP) process. WSPs were developed to assess and manage risk in drinking water systems, and include an assessment of risks within a drinking water system and the surrounding environment that may affect water quality (Bartram et al., 2009). WSPs are also a stakeholder-based process that aim to bring together relevant partners to address those risks. A WSP-style process could provide a potential framework for looking at irrigation water quality in a more systematic manner that would not require a regulatory approach. Applying this type of approach to agricultural water would include a systematic identification of potential risks to irrigation water quality. This would encompass a wide variety of issues, including examples such as identifying point and non-point sources of contamination and seasonal variation in water quality for surface waters. Examples of potential ground water issues that could be included are well construction techniques, the presence of abandoned wells that could provide conduits to the subsurface and surface waters entering wells during flooding. Ground water-surface water interactions are another example, as ground water under the influence of surface water may become contaminated. The type of irrigation used may also potentially influence whether any contamination in irrigation water reaches crops. In addition, broader environmental factors, such as heavy precipitation events, may influence irrigation water quality, as these events have been associated with waterborne disease outbreaks (Curriero et al., 2001). The specific issues facing particular farms will vary, but a preventive method based on a WSP type of process provides a systematic way to approach identifying potential risks to irrigation water and developing prevention strategies.

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