PRODUCE SAFETY PROJECT ISSUE BRIEF:

STANDARDS FOR IRRIGATION AND FOLIAR CONTACT WATER

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Introduction

Fresh and fresh-cut produce, including tree nuts and dried fruits, and specialty-niche crops (i.e. ethnic crops, culinary herbs, international horticultural foods) often are irrigated with ground water, surface water, and reclaimed or recycled water throughout the U.S. (USDA NASS, 2008 and 2009). As reviewed by Carr et al. (2004), it is estimated that 18% of worldwide cropland is irrigated, producing 40% of all food. A significant portion of irrigation water is wastewater. For example, estimates project at least 20 million hectares in 50 countries are irrigated with raw or partially treated wastewater. (Carr et al., 2004). Between 2003 and 2008 the total irrigated acreage for U.S. farms and ranches increased almost 5% (NASS, 2009). Included in this trend were a 12% increase in ground water use and 22% increase in use of on-farm surface water sources. In the recent Census of Agriculture, NASS reports almost 10 million acres of commercial farm fruits, nuts, and vegetables in the U.S. and over 7 million of these under some form of irrigation management. California dominates the scale with almost 5.5 million acres of irrigated acres devoted to specialty crop production, which includes all stable, low moisture, and perishable horticultural food crops. Texas and Washington have substantial acres under irrigated specialty crop production and, proportionally, essentially all vegetable crop production in Arizona requires managed irrigation (See Table 1).

	Distribution of Irrigation Methods {2008 NASS Survey} (2007 Response in 1000's acres)			
	Gravity (flood)	Sprinkler	Drip/Trickle	Sub-irrigation
United States	22,018	30,877	3,756	200
Arizona	764	178	54	—
California	4,190	1,367	2,336	66
Florida	473	185	549	56
Texas	1,032	4,192	173	500
Washington	200	1,379	138	—

Table 1. Overview of irrigation methods in key fruit and vegetable producing states.

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As greater attention over the past 20 years has been directed to the rising evidence and role for fresh produce in illness and outbreaks, pressure for increasingly specific and prescriptive food safety programs and associated standards has come from several directions. Though long debated internally and externally, the events surrounding outbreaks between 2005 and 2007, exemplified by the *E. coli* O157:H7 outbreak on spinach and processed lettuce in 2006, accelerated the efforts of produce industry leadership to define practical, meaningful, and measureable prevention practices and standardized audit criteria. These are often referred to as the 'metrics' associated with Good Agricultural Practices (GAPs) and Commodity–Specific Guidance documents (CSFSGLLGSC 2006; CSFSGLLGSC 2008; CSG T-GAPs 2006;CFFSGFTSC 2008; CSG Tomato 2009). Several factors converged to convince many within the lettuce and leafy greens industry to forge and implement such standards, which would be the preliminary benchmarks for monitoring and compliance assessments. The prevailing approach was to adopt science-based standards anchored to a recognized authority or established metric for risk reduction wherever possible. One of the most contentious of these emerging metrics was the debate over irrigation water standards.

Eventually, the lettuce and leafy green industry sector developed a supply-side self-mandate that defined the parameters for irrigation water sampling and set uniform decision and action-points derived from these quality standards. These microbial limits were based on the United States Environmental Protection Agency's (EPA) recreational water quality criteria for full body contact (US EPA 1973). Though not universally embraced, eventually microbial limits, compliance criteria, and a decision-tree for corrective actions were adopted (CSFSGLLGSC 2006). Though surrounded by uncertainty as to the validity or applicability of the approach, these metrics were acceptable to their customers (fresh processors or foodservice and retail buyers). The hope was that having a system in place also would help restore confidence among consumers. Several foodservice and retail-led groups adopted the same or parallel standards for irrigation water. Though already in motion or adopted by other commodities, the large and economically devastating produce outbreak associated with *Salmonella enterica* sv. Saintpaul in 2008 had a pronounced impact on the fresh tomato industry to expedite uniform state regulated (CSG T-GAPs 2006), grower/handler association (CFFSGFTSC 2008), and national standards (CSG Tomato 2009), including irrigation water.

The focus and objective of this Issue Brief is to review the challenges and approaches to establishing functional and meaningful standards and microbiological limits for irrigation water used in the preharvest phases of fresh-consumed horticultural foods. Limited reference to foliar contact will be included relative to current practices regarding water quality and timing of applications. Where citation to scientific journal publications, other forms of peer-reviewed works, or publically available databases is not available, the author feels reference to reports of unpublished data or industry practice is justified to allow broader appreciation of the issues.

Overview of the Issue

For most individuals, the term irrigation water is fairly self-evident. Foliar contact water in the context of preharvest (crop production) management applies to many less familiar practices including;

- **Pesticides** – typically insecticides, fungicides, and bactericides including microbial pesticides (biological control agents); may include herbicides at tolerant crop stages, though rarely.
- **Nutrients** – various macro and micro-plant nutrients (fertilizers) applied to aerial portions of plants for absorption rather than to the soil.
- **Growth regulators** - plant growth regulators (hormone-like substances) applied at various stages of plant development and for diverse purposes, generally to improve quality and marketability.
- **Manure teas and compost teas** – various infusions with pesticidal, nutrient, and growth regulator benefits reported.
- **Thinning aids** – plant growth regulators (hormone-like substances) applied at early stages of fruit set and development to reduce the crop load and increase individual fruit size and quality.
- **Harvest aids** – a wide range of low volume applications of potable water or water plus acidulants, chelating agents, or other compounds, typically at harvest, but included here in foliar contact
- **Frost control** – one strategy to protect certain sensitive crops from frost or freeze injury is to insulate the plant, and often fruit, with ice by applying continual foliar wetting with sprinklers or micro-misters
- **Anti-transpirants** – water soluble chemicals applied to foliage to reduce water loss
- **Dust control** – large volumes of water applied to unpaved farm access roads and harvest buffers to reduce dust, primarily from equipment and other farm traffic.
- **Microenvironment management** – water applied by various modes, though often micro-sprinklers or micro-misters to create evaporative cooling for quality management

The microbiological quality of water at the source and during storage, conveyance, and distribution on-farm can be highly dynamic. The flux in levels and diversity of pathogens is affected by many, often complex, interacting factors including climatic events, seasonal weather patterns, adjacent land uses, wildlife activities or migration, hydrogeologic characteristics of aquifers, agricultural activities, recreational activities and easements within agricultural settings and other forms of urban encroachment or urbanization, to name just a few.

Irrigation water is a potential source for produce contamination

Irrigation water and any foliar applied water, with intimate contact to the developing or mature edible portions of fresh produce, has long been recognized as one of the most plausible and probable sources of fresh produce contamination with pathogens of concern for human health (Geldrich and Bordner, 1971; Hillborn et al., 1999; Ruiz et al., 1987; Sadovski et al., 1978; Wheeler et al. 2005).

The detection of pathogens in watershed run-off, recreational water, and irrigation source water, both domestically and globally, such as *Salmonella*, *E. coli* O157:H7 and other shiga-toxin producing *E. coli* (STEC), *Shigella*, hepatitis virus A, norovirus, *Cryptosporidium*, *Campylobacter*, *Listeria*, and others is well documented in recent overviews and reviews (Aruscavage et al., 2006; Avery et al., 2008; Doyle and Erickson, 2007; Ferguson et al., 2003; Gerba, 2009; James, 2006; Winfield and Groisman, 2003). The potential for persistence of these pathogens for various durations in research studies, once brought into contact with phyllosphere and rhizosphere surfaces of horticultural crops by artificially contaminated irrigation water, has been frequently reviewed and cited as a major risk factor and concern (Brandl, 2006; Fan et al., 2009; Hanning et al. 2009; Sapers et al., 2006; Teplitski et al., 2009). Recent field studies and investigations of contamination that resulted from the use of partially treated sewage effluent for vegetable irrigation (Ibenyassine et al., 2007; Rai and Tripathi, 2007) have added to the body of literature, primarily from the 1970's.

Risks Associated with Irrigation Water

According to the most recent available NASS census (USDA NASS 2008 and 2009), over half of the total irrigated acreage in the United States (52.5 million acres) was applied by overhead irrigation. Among overhead-irrigated acreage, about 113,000 acres were berries, 81,000 acres were tomatoes, 162,000 acres were lettuce and romaine, and 1,110,000 acres were other vegetables. It was not possible to discriminate whether the source of irrigation water was surface or ground water for these crops, but regular use of surface water delivered through overhead irrigation equipment has been reported in a number of surveys of fresh fruit and vegetable producers.

Potential direct and indirect contamination of fresh produce with pathogenic microorganisms can result from contact with irrigation water, feces, soil, inadequately composted manure, dust, wild and domestic animals, and human handling (FDA 1998 and 2007). Irrigation water sources include wells, ponds, rivers, streams, municipal water sources, and reclaimed (treated wastewater) water. The complexity of on-farm irrigation water management is easily be appreciated by even a cursory list of the many ways irrigation water can be applied including overhead, furrow, flood, seep ditches, surface drip, and subsurface drip to name a few (Steele and Odemeru, 2004; Suslow 2002 and 2003.) Likelihood of contamination is also dependent on the commodity being grown. Stine et al. (2005a and 2005b) in conducting a quantitative microbial risk assessment noted that the irrigation method and type of produce grown influenced the transfer of microorganisms to produce through irrigation water. In related studies, Choi et al. (2004) and Song et al. (2006) utilized only subsurface drip and furrow irrigation and still found organisms could be transferred to the commodities through irrigation water. In the United Kingdom, a survey of salad (leafy greens) producers showed that the primary irrigation source was surface water delivered through overhead application with very limited monitoring of water quality. This study also found that the gap between the last application and harvest may be <24 hours in many cases. One concern this study discusses is the fact that rivers used for irrigation also serve as deposition sites for the majority of the United Kingdom's treated urban wastewater (Tyrell et al., 2006).

Irrigation water, which can be a source of pathogenic microorganisms, can ultimately contaminate agricultural products (Beuchat and Ryu, 1997; Gallegos-Robles et al. 2008; Guo et al., 2002; Solomon et al., 2002a and 2002b; Thurston-Enriquez et al., 2002). A variety of fecal contaminants and pathogens such as *E. coli*, *Salmonella spp.*, *Listeria* spp., *Crytosporidium*, and enteric viruses have been isolated from irrigation water and associated sediments (Borchardt et al., 2009; Jiang and Wu, 2004; Jiang et al., 2007; Loge et al., 2002; Lu et al. 2004; Morace et al., 2002).

In their investigation following the 2006 *E. coli* outbreak in spinach, the California Department of Health Services (CDHS) and U.S. Food and Drug Administration (FDA) identified contaminated irrigation water as a possible source of *E. coli* O157:H7 (CDHS FDA, 2007). Detailed analysis of the regional hydrogeological characteristics and specific weather conditions contemporary with the production of the implicated spinach suggested sub-surface transfer (discussed briefly later) as the cause of irrigation water contamination (Gelting, 2007). The spinach-related outbreak of *E. coli* O157:H7 in 2006 generated uncertainty among consumers and led to reduced consumption of packaged spinach (to 43% of prior consumption). Sales of packaged salads remains impacted, around 20% below prior periods (Calvin, 2007). This pivotal outbreak, for which economic consequences were estimated to be over $200 million (Calvin, 2007), is thought to have been caused by a single contamination event in a single spinach field (CDHS FDA, 2007). Though the outbreak was not conclusively linked to contaminated irrigation water, it contributed directly to demand for safety standards in the production of fresh produce. More recently, the CDC and FDA also identified irrigation water from a Serrano pepper farm in Mexico as a possible source of the 2008 *Salmonella enterica* sv. Saintpaul outbreak in the U.S (CDC, 2008). Lack of public confidence has clear economic impacts and undermines programs by public health officials to promote consumption of fresh fruits and vegetables by Americans (www.mypyramid.gov).

Sources of Water

While there is concern for the quality of water designated for preharvest use in the major production regions of the U.S., surface water is generally viewed as more susceptible to fecal contamination than is ground water. Irrigation with surface water is expected to pose greater risk to human health than irrigation with water from deep aquifers drawn from properly constructed and protected wells. However there are clear concerns based on well-water surveys and the prevalence of human illness associate with contaminated ground water, particularly enteric viruses (Gerba and Smith, 2005; Pillai and Pillai, 1998; Sinclair et al., 2009). The potential for ground water contamination from surface events, such as flooding or storm-related run-off from areas of concentrated manure accumulation, manure lagoons, or sewage treatment facilities, is well characterized (Oron et al., 2001; Gerba, 2009; Ibekwe et al., 2004 and 2006). Soil and hydrogeologic characteristics of a region, particularly macro-pores and macro-channels can contribute to significant risks of sub-surface flow from surface contamination sources to both surface and ground water. The role of such features in waterborne outbreaks may be obtained in Dorner et al. (2006). During the outbreak investigation in 2006, a detailed CDC report provided suggestive arguments to associate atypical water level differentials between surface and ground water as a source of contamination of one well near the implicated field (Gelting, 2007). Though highly controversial and speculative, this analysis was the catalyst for dialogue between produce industry, public health officials, and regulators to evaluate the means to address regional ground water quality and protection concerns.

In addition, in some regions or within individual operations, even very deep wells may have points of surface water entry due to discontinuity of the dense clay barrier or at casing perforations designed for water capture at much shallower depths than the aquifer below an impervious clay layer. This may be part of the well design to take advantage of seasonal water availability above the zone of aquifer re-charge. Although there are additional sources of ground water contamination, one worth mentioning here is aquifer contamination from inoperative or abandoned wells. Investigations of the cause of wells that chronically fail coliform testing criteria have been associated with surface run-off intrusion to abandoned and uncapped bore-holes that were not on a farm map and not included in seasonal testing programs.

In most cases, the microbiological quality of surface water used for irrigation is not known because it is not tested in any meaningful frequency. Over the past three years, in particular, this situation has substantially changed in many regions of fresh produce production in the U.S. extensively in California and Arizona and in many areas that are major sources of fresh produce imports to the U.S. However, the overwhelming majority of this database is privately and tightly held. It is worth noting that "public disclosure" of elements and aspects of this data set, representing tens of thousands of individual irrigation water samples enumerated for *E. coli*, has been made in industry association annual meetings and workshops. Therefore, anecdotally one may say that the preponderance of data indicates that irrigation water in western regions of the U.S., the major source of domestic lettuce and leafy greens and other cool season vegetables, has very low levels of the currently accepted microbiological water quality indicator not related to wastewater treatment standards.

From the disclosed data it is not possible to distinguish the proportion of samples represented by groundwater or various types of surface waters. The comparability of quantitative data is equally unknown, at this time, as variation in source of the samples, sampling technique and initial volumes, sample handling, sub-sampling, test methods, and specifics of test protocols for enumeration are recognized as a potentially problematic.

Questions about the Suitability of Recreational Water Standards for irrigation water

A limited, and arguably outdated, set of indicators of fecal contamination has been used by the fresh produce industry to assess the suitability of water used in preharvest crop production up to the point of harvest. Many regional GAP and CSG systems have relatively recently adopted EPA recreational water quality criteria for establishing action thresholds, in the absence of actual risk-based data based on irrigation water (CSFSGLLGSC 2006 updated 2009). As internal and external pressure is exerted for national standards, a simple approach has been to adopt these EPA criteria. Without a baseline of data to assess the applicability of the approach, it is not possible to assess the significance of the chosen metrics in contributing measurably to public confidence and actual safety goals.

Recreational water standards, based on *E. coli* or *Enterococcus* population density in the water body, were developed according to science-based criteria (US EPA 1973 and 1996). The subset of hierarchical criteria addressing health risk, selected by the produce industry, was the most stringent within the EPA matrix for testing. These Most Probable Number (MPN) values were calculated from observed human health risk posed by full-body contact at swimming beaches that were impacted by human sewage. Although the contamination sources, water type, and route of infection are dramatically different between swimming at beaches and consumption of fresh fruits and vegetables, the recreational water criteria are easily accessible and are anchored to a recognized federal agency rather than a produce industry-sponsored study or self-generated data assessment. In the absence of deep scrutiny this starting point for establishing industry performance standards seemed palatable to the general public.

The irrigation water quality standards first adopted by the LGMA in California (CSFSGLLGSC 2006; updated 2009), based on these recreational water criteria, have been migrating to other states. A prior similar approach, in 2001, with modifications to the EPA values, was established in British Columbia, Canada. The rationale for adopting a more restrictive set of crop dependent standards for irrigation of produce consumed raw (without cooking or equivalent terminal kill step) was explained in great detail (Marr, 2001). To paraphrase the California standards, water used for overhead irrigation must have a 5-sample rolling geometric mean *E. coli* density lower than 126 MPN or CFU/100 ml and no sample should have an *E. coli* density greater than 235 MPN or CFU/100 ml. Similarly, water used for drip or furrow irrigation must have a 5-sample rolling geometric mean *E. coli* density lower than 126 MPN or CFU/100 ml and no sample should have an *E. coli* density greater than 576 MPN or CFU/100 ml.

The science behind the recreational water criteria was intended to maintain a risk of gastrointestinal illness lower than eight cases per 1,000 swimmers at freshwater beaches (US EPA 1973; Marr, 2001) based on exposure to point-source, untreated human wastewater discharge or spill; thus, the criteria may not be relevant to irrigation water. As designed, the criteria were further based on correlation with recent fecal contamination events and research on the kinetics of indicator die-off to ambient levels. The EPA criteria, as they were not intended to apply to risks associated with irrigation management of edible crops, do not take into account the kinetics of die-off during post-irrigation intervals and exposure to environmental stresses associated with crop production. Controlled environment and field studies conducted within Quantitative Microbial Risk Assessments (QMRA) for irrigation water:commodity suggest a variable interval between a foliar contamination event due to irrigation and relative risk of illness (Stine 2005a and 2005b). Common recommendations of two-weeks to allow for appropriate die-off remain to be thoroughly tested. Though not yet subjected to peer-review for publication, recent on-farm studies with attenuated *E. coli* O157:H7 in the Salinas region of California indicate a rapid death curve but extended survivor tail following a simulated single foliar contamination event on lettuce and spinach (Harris 2008 and 2009; Koike et al. 2008 and 2009).

Non-point sources of the indicator *E. coli* and the recognized potential for environmental growth and persistence cast a shadow of the validity of universally perpetuating this specific metric. Results of two recent studies (Harwood et al. 2005; Duris et al., 2009) provide further evidence to question the validity of current indicators of sanitary water quality as indicated by *E. coli* density and its correlation to detection of *E. coli* O157:H7, *Salmonella*, and enteric viruses. Thus, though *E. coli* density may indeed be indicative of public health risk from all gastrointestinal pathogens, it may not indicate presence of select key food borne pathogens. In fact, Winfield and Groisman (35) concluded that "different rates of survival of *Salmonella* and *E. coli* in nonhost environments suggest that *E. coli* may not be an appropriate indicator of *Salmonella* contamination."

For its part, recognizing the limitations of the current irrigation standards, the FDA's recently released Draft Commodity Specific Guidance documents for leafy greens, melons and tomatoes (FDA 2009) provides no specifics, critical limits, or metrics based on indicators or pathogen prevalence in a standardized sample volume of any size. Producers are held to self-determination of the broadly applicable position that water should be "of appropriate quality for its intended use, obtaining water from an appropriate source, or treating and testing water on a regular basis and as needed to ensure appropriate quality." It is an understandable position for a regulatory authority in the face of substantial scientific uncertainty.

Many other indicators of water quality including various human, ruminant, and avian bacteria, coliphages, environmental chemicals, sterols, detergents, caffeine, specific nucleic acids, and a host of other approaches are well established or currently under investigation. None are perfect and most are currently beyond the economic or practical availability of a routine test for the fresh produce industry. It seems a certainty that emerging research will provide innovative options for irrigation water testing in the near future.

Test methods and the challenge of strict "metrics"

A full discussion of the various approved test methods for drinking, environmental, waste-treatment, and recreational water monitoring would be too expansive for this Issue Brief. A key concern generated by the need to comply with strict critical limits associated with current industry metrics is the specificity of the enumeration method as applied to the intended purpose and sample matrix. Having accepted generic *E. coli* as the standard for monitoring of irrigation water and numeric limits for compliance and non-compliance, it is natural to be concerned that the accuracy of the test has been validated. As mentioned above, the issue is not generally problematic as the majority of irrigation sources test well below the current standards. Basing actionable thresholds on a rolling geometric mean reduces the chance of a temporary increase in indicator levels triggering severe economic hardships. However, for individual growers or regionally among growers along a common irrigation source or system, hitting a single sample value above the strict threshold, for example 235 MPN/100 ml for overhead irrigation, is a critical event. Avoidance of hitting these meaningless breakpoints, relative to actual risk, invites temptation towards unethical practices. Simply put, validated test methods for *E. coli* estimations that require sample incubations of 35 or 37C may be perfectly reasonable and sufficiently specific for dairy, meat, poultry, and other foods or environmental testing but are too permissive for applications to irrigation water testing and other produce-related applications. Commercial tests vary in their specificity for enumerating *E. coli* and positive reactions are well recognized among related non-pathogenic bacteria commonly found in water sources, on plant surfaces, and in soil. Even at warmer temperatures, more selective for fecal coliforms (aka thermotolerant coliforms), such as 42.5 to 44C, non-*E. coli* bacteria may be present and elevate the test outcome above a threshold limit for termination of irrigation with a water source or product acceptance. Fortunately, there are validated commercial tests available that have been found to have a very high selectivity for *E. coli*. Standards to meet the required performance specificity for irrigation water should be adopted and embodied in CSG's for fresh produce.

Current water quality standards poorly define the relation between indicators, pathogens, and risk of consuming produce

Though irrigation water previously has been studied extensively (Gerba, 2009), these studies were concerned primarily with chemical rather than microbiological water-quality parameters. As a result, the knowledge gap regarding sanitary quality of irrigation waters is nationwide. Data are particularly scarce in areas where the fresh produce is direct marketed because many of these producers are not under industry pressure to test their irrigation water. The current lack of uniform standards that have accepted and compelling predictive value, relative to cost, in relation to known pathogen risk is a key barrier to implementing testing programs among growers. Public attention to recent outbreaks of foodborne illness led the U.S. produce industry to search for an authoritative source of standards to preliminarily set the microbiological safety of irrigation water. The choice to adopt EPA recreational-water criteria at the time, and especially in retrospect, did not appear to be a sound, science-based selection for direct application to irrigation water; however, in the absence of a publicly available database from extensive testing it was deemed the best option.

The risk to consumers by contaminated irrigation water due to external and, possibly, internal contamination of leafy greens has been recently reviewed in some detail (Brandl, 2006; Sapers et al. 2006; Fan, 2009; Gerba, 2009). In the United States, federal standards for irrigation quality do not yet exist and international standards are considered too permissive (FDA, 1998).The World Health Organization standard of <1,000 CFU fecal coliform/100 mL water, which may be used on fresh produce without restrictions (WHO, 1989; Buchanan and Dennis. 2001) is based on empirical epidemiological evidence not recognized as acceptable to U.S. public helath agencies. Despite best efforts and understandable limitations, current irrigation water quality criteria are among the most universally relevant, but the least satisfactory standards have been adopted. Generic (commensal) *E. coli* have been used as the indicator organism (IO) of choice; however no clear and supportable standards have been available to establish microbial limits or criteria that define suitable versus unacceptable quality for the diverse sources and modes of application.

The adoption of meaningful and predictive standards or criteria, particularly for irrigation water quality, is significantly hampered by the apparent lack of correlation between indicator coliforms or generic *E. coli* levels and the detectable presence of pathogens such as EHEC. Micro and mesocosm studies (Sherer et al. 1992; Anderson et al. 2005) have demonstrated the severe limitations of popular IO's, including commensal *E. coli*, in predicting pathogen presence or correlating to proportional survival following fecal contamination. Many reports have demonstrated that *E. coli* can survive and multiply in irrigation water, wastewater, subtropical sediments, and mineral water. Persistence of IO in the absence of detectable levels of pathogens and secondary growth, strongly suggest that the use of current IO is compromised and renders decision-making or rule-making based on presence/absence or numerical thresholds borrowed from stringent recreational water quality standards an unnecessarily self-penalizing practice.

Fresh produce growers need the ability to differentiate high-risk irrigation water from low-risk irrigation water

Effective guidelines for health protection should be practical and adaptable to fresh produce production. Commodity, crop management practices, climate and region, other agro-ecological factors, and other modifiers should be evaluated in setting microbiological limits. WHO (Carr 2004 and 2005) has recommended inclusion of the following elements: (1) Evidence-based health risk assessment; (2) Guidance for managing risk (including options in disinfection treatment); and (3) Strategies for guideline implementation (including progressive implementation).

Suggestions for federal standards for irrigation water quality have, often mistakenly, assumed that water quality requirements for the use of wastewater in unrestricted irrigation are the appropriate benchmark. Wastewater reclamation standards that apply to fresh produce uses are far stricter than surface water quality requirements for unrestricted irrigation (Carr, 2005). Surface water in many places would not meet the EPA standard for irrigation with treated wastewater of ≤2.2 total coliforms per 100 ml. Long-standing guidance for surface waters used for irrigation specify ≤1,000 fecal coliform per 100 ml (USEPA, 1973). This poorly defined class of indicators and allowable population levels are now held to be unacceptable for fresh produce production where intimate contact with the edible plant parts is likely or inevitable. Without going into details, the higher standard for wastewater treatment is, at the same time, critical for human sewage handling due to known contamination potential of high concentrations of pathogens and commonly non-applicable for most irrigation sources. The low levels of indicators required for applications of reclaimed water are predicated on their validity as satisfactory evidence for a functional disinfection process control. Once the total coliform numbers drop to the specified level, from several orders of magnitude greater initial counts, the correlative data predicts pathogen levels will have dropped to non-detectable or safe levels in the water. While aspects of wastewater risk assessment studies and uses remains controversial, the rationale for the more stringent standards based on the certainty of pathogen contamination of the source material is sound.

Foliar Contact Water Quality

The general issues and potential involvement of foliar applied water in preharvest pesticide applications in product contamination, revealed during outbreak investigations, is well covered in Brandl (2006), Fan et al. (2009), Doyle and Erickson (2007), Suslow et al. (2003) and within several chapters of James (2006), Sapers et al. (2006), and Fan et al. (2009). Human pathogens such as *E. coli* O157:H7 and non-typhoidal *Salmonella* have been shown to survive and potentially grow in many agrichemicals applied to aerial plant parts including foliar and fruit sprays (Guan et al. 2001 and 2005). The concerns for the safe production and use of manure and compost teas may be derived from the Issue Brief: Composting Criteria for Animal Manures.

The expectation that foliar applications for crop management of fresh produce will use only potable sources is widely held and largely followed in the U.S. However, it would be irresponsible within this brief discussion not to at minimum acknowledge that convenience and human nature sometimes dictates that water is drawn from the closest source to the point of application. Refilling spray tanks with water pumped or, in the case of very small operations, scooped into back-pack sprayers from uncharacterized surface water sources does happen. A further risk introduced from this potentially hazardous practice is the growth of pathogens within the application equipment as water temperature rises, especially if excess material is held in the tank for hours or overnight or if spray tanks and lines are not cleaned out after use. Even surface water sources that are tested periodically may have unsuspected sources of contamination in sediments that are picked up by improper placement of PTO or pump-driven siphons.

Factors that affect contamination potential between sampling intervals

Water sampling frequency and timing relative to irrigation events are key limitations in the application of any testing program linked to food safety management for fresh produce. Irrigation water is mistakenly assumed to be a highly controllable farm input. This is especially true for surface water sources and, realistically, of greater concern for naturally-moving sources (rivers, creeks) or delivered/conveyed water systems (irrigation district canals) whose dynamic quality is largely or entirely beyond the control of the grower. These unique and dynamic hazards of temporal pathogen contamination have been extensively researched (Maki and Hicks, 2002; Wang and Doyle, 1998;

Winfield and Groisman, 2003) and recently reviewed by Gerba (2009). The key unique risk factors relate to sediments as a reservoir for pathogen survival and their redistribution or de-stratification during turbulent flow or mechanical disturbances. For some water sources, wind-driven channeling waves or storm-driven disturbances can cause significant localized or broad-scale mixing at various water:sediment boundaries. Additional sources of sediment suspension include the physical features of natural bed contours under high flow rates, canal design, especially branch-points, and various weirs, diversions, on-farm irrigation flow-control gates, and return-flow systems. Mechanisms for re-introduction of sediments are a shared concern with on-farm reservoirs which also require in-season management but the distinction, for this section, is the degree of control and planning or notification of human-derived disturbances.

The potential for human-derived disturbances of natural water sources and irrigation district systems is primarily a consequence of periodic maintenance including dredging, construction, and removal of algae, aquatic weeds, bull-rushes, and bank vegetation. Sediment dredging can temporarily introduce pathogen-laden silt and clay particles into the flow-stream and be carried long-distances. Growers have identified inconsistencies in agency notification of such maintenance activities, especially of concern during in-season intervals, as compromising their Sanitary Survey assumptions for water source hazards in GAPs plans. The timing of sampling relative to any such disturbance and an irrigation event strongly affects the opportunity to identify a potential risk in the absence of such regionally coordinated notification. Growers may not have alternative water sources during these periods or may have irrigated a crop prior to receiving an on-farm test result suggesting a potential up-flow problem. Some types of local construction projects (i.e. bridge support stabilization) and regional in-season maintenance of irrigation canals (dredging and algal scraping) is unavoidable and has caused non-compliant water test outcomes.

Algal control and disturbances of macro-algae flocs is an interesting and emerging topic for hazard analysis but beyond the scope of this Issue Brief. In brief, algal mats in irrigation water source reservoirs and distribution systems have long been recognized as undesirable from a practical management perspective. Byappanahalli et al. (2003 and 2009) reported that leachates from the common macro-algae *Cladophora* support the rapid *in vitro* growth of *E. coli*. Survival of *E. coli*. on collected dried thalli exceed six months at 4oC. Re-growth of *E. coli* following rehydration of dormant thalli reached levels exceeding log 8.0 CFU g -1. More recently, Ishii et al. (2006), from the same group, provided details of this potential reservoir for contamination and growth in natural lake waters. Macro-algae in recreational water bodies have been documented to seasonally harbor fecal indicator bacteria, *Salmonella*, *Shigella*, *Campylobacter*, and shiga-toxin producing *E. coli* (STEC) on free-floating flocs and mats attached to shoreline rocks, including environmentally-dried algal mats below the high water mark. Algal flocs and mats are speculated to serve as transient or seasonal habitat for these pathogens, providing nutrients and protection from lethal UV exposure and predation. In addition, over-wintering or contra-seasonal survival on dried mats may serve as a re-contamination reservoir and one source of re-introduction to water during in-season recharge. Recent preliminary surveys, conducted during 2008-09 seasons in California, have demonstrated the infrequent but positive recovery of STEC in association with algal flocs in irrigation canals (Suslow, unpublished data). These detection events have been largely restricted to late season sampling dates, consistent with periods of Harmful Algal Blooms (HAB) that clog waterways. Standard grab-sample (100ml) and larger volume assessments (5-10L) of the bulk water collected at the same time were negative for STEC in these studies. It will be important to determine whether algae are an environmentally significant contributor to IO populations in diverse irrigation source waters, independent of a detectable co-contribution to seasonal presence, survival, and periodic bloom-growth of pathogenic *E. coli* and *Salmonella* spp.

Mechanical removal and chemical controls have the potential to introduce pathogens into the bulk water used for irrigation at intervals between sampling dates or coincident with an irrigation event. Algal fragments may be picked up in water intake siphons and carried with the irrigation or foliar contact water, if taken from a surface source. Systems which employ pre-irrigation filters may largely remove particulates but our studies conducted to date have shown limited reduction in total bacterial removal by standard filtration alone. Whether environmental conditions and/or HAB development and mass-physiology trigger episodic release of fecal indicators and pathogens to water as planktonic cells or aggregates remains to be determined. The release of fecal indicators, the more common algal-associated enteric bacteria, could substantially and artificially impact water sample test results to levels above current standards which assume a recent fecal contamination event is indicated.

An interesting additional but uncertain factor that may influence irrigation water quality in some regions is the use of fish for aquatic weed control in government managed irrigation distribution networks. An example is the use of grass carp (*Ctenopharyngodon idellaby*) in the Imperial Irrigation District (IID) in southernmost California. Started as a research project in 1981, since 1985 the IID has been stocking sterile, triploid grass carp in their canal systems. Various naturally populated surface water sources have fish and many other forms of associated wildlife and domestic animals that may indirectly affect water quality. However, this example merely points out lack of specific information available to assess relative risks in relation to a category of source; river water vs. concrete-lined irrigation district canal.

Future prospects: is a uniform standard attainable?

Direct detection of specific pathogens is both a way to validate and an alternative to, E. coli-based standards

A single national standard for irrigation water quality applicable to all commodities, regions, and scales of production seems both unwise and unattainable without creating hardship to the fresh produce sector or allowing sporadic unacceptable levels of risk to consumers. Just as science-based criteria are required for recreational waters, science should be applied to formulate flexible and risk-based criteria for irrigation waters. One of the key on-going points of debate regarding these standards, including sampling frequency and location, is the sense of a large disparity between risk associated with ground water from deep aquifers and surface water. In some supplier qualification schemes, well water is held to a much higher standard than surface water, approaching drinking water microbiological criteria, because it is generally attainable. Growers with access to such high quality water from well protected wellheads have argued that frequent or continuous monitoring for *E. coli* levels merely generates a long series of zeros (<2.2 MPN/100ml). Counter arguments include the concern that sampling at the wellhead, while important, is insufficient and regular testing of the distribution system, especially if a sub-soil surface conveyance to on-farm risers and valves, at the point of application (i.e. gated pipe, sprinkler head) in some standardized pattern is warranted. However, this is more an issue of prevention and integrity of water quality protection practices rather than a source assessment. Regardless, these and other variations in BMP's for irrigation water quality sampling and testing remain to be resolved and harmonized.

Before expanding the current recommendation of *E. coli*-based standards for irrigation water to federal regulations, it will be important to assess whether any *E. coli*-based criterion would be relevant to indicate the presence of specific pathogens. The alternative may be to use direct detection of the target pathogens to indicate sufficient quality for waters used to irrigate fresh produce. A set of recommended practices for sample size and performance-tested methods may be derived from published studies, such as Castillo et al. (2004) and Loge et al. (2002). In the later study, the two principal factors influencing the direct detection limit for several key pathogens was sample volume, liters rather than 100ml, and the presence of inhibitory compounds in the purified nucleic acid extracts.

One solution for some growers faced with the uncertainty of irrigation standards, or the repeated failure of the only available water source to meet the metrics for indicator bacteria, has been to treat the water. Two of the more popular treatments, though still a very limited practice across the U.S., are injection of calcium hypochlorite or chlorine dioxide. The design of the dosing system is, in general, to bring the indicator *E. coli* levels within a compliant range and less commonly to meet drinking water criteria. For irrigation of many key crops, the volumes of water being pumped for overhead irrigation, for example, may be in excess of 1500 gallons per minute. In California and Arizona farms where this is being applied, water quality is generally good and the disinfectant demand is low. Therefore, low doses, 2-5 mg/L (2-5 ppm) of active ingredient are sufficient. This lessens the concern for detrimental effects on the farm soil or the environment from disinfection by-products (FAO/WHO 2009) in the short-term. Concerns remain for chronic effects of large-scale use over long periods of time on the degradation or soil quality and negative impacts on wildlife and habitats. Other water treatments with minimal concerns, such as ozonation and UV, are too costly for most producers but have been installed with low flow systems on high value crops including precision drip delivery for berry production.

Effective control of irrigation-water quality will depend on the economics of control. Producers cannot make informed decisions, given the current state of information regarding irrigation water, about choice of commodities to grow, at what time and from what source to irrigate, and whether to sacrifice yield for safety by choosing not to irrigate with high-risk water. Among current knowledge gaps are: (1) the sanitary quality of many irrigation water sources, (2) the relation between density of traditional fecal-indicator bacteria (such as *E. coli*) and the risk of encountering key foodborne pathogens (such as *E. coli* O157:H7 and *Salmonella*), (3) the remediation costs for contaminated water prior to irrigation, 4) the willingness of producers to adopt and enforce variable irrigation water quality standards.

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Citations

Anderson, K. L., J. E. Whitlock, and V. J. Harwood. 2005. Persistence and Differenatial Survival of Fecal Indicator Bacteria in Subtropical Waters and Sediments, 71: 3041-3048.

Aruscavage, D. L., K. Miller, S. LeJeune, J.T. . 2006. Interactions Affecting the proliferation and control of human pathogens on Edible plants. . Journal of Food Science 71:89-99.

Avery, L. M., A. P. Williams, K. Killham, and D. L. Jones. 2008. Survival of Escherichia coli O157:H7 in waters from lakes, rivers, puddles and animal-drinking troughs. *The Science of the total environment* 389:378-385.

Borchardt MA, Spencer SK, Bertz PD, Ware MW, Dubey JP, Alan Lindquist HD. 2009. Concentrating Toxoplasma gondii and Cyclospora cayetanensis from surface water and drinking water by continuous separation channel centrifugation. Journal of applied microbiology.107:1089-97.

Brandl, M. T. 2006. Fitness of human enteric pathogens on plants and implications for food safety. Annual Rev. Phytopath. 44:367-392.

Buchanan, R.L. and S.B. Dennis. 2001. Microbial risk assessment: a tool for regulatory decision making. *J. Association of Food and Drug Officials*, 65 36-46.

Byappanahalli, M., Shively, D., Nevers, M., Sadowsky, M., and R. Whitman. 2003. Growth and survival of *Escherichia coli* and enterococci populations in the macro-alga *Cladophora* (Chlorophya). FEMS Microbiology Ecology. 46:203-211

Byappanahalli, M., Sawdey, R., Ishi, S., Shively, Ferguson, J., Whitman, R. and M., Sadowsky. 2009. Seasonal stability of Cladophora-associated Salmonella in Lake Michigan watersheds. Water Research 43:806-814

Calvin, L. 2007. "Outbreak Linked to Spinach Forces Reassessment of Food Safety Practices. 5:24-31. www.ers.usda.gov/AmberWaves/June07/Features/Spinach.htm

Carr, R.M., Blumenthal, U.J. and D. D. Mara. 2004. Guidelines for the safe use of wastewater in agriculture:

revisiting WHO guidelines. Water Science and Technology. 150:31-38.

Carr, R.M. 2005.WHO Guidelines for safe wastewater Use: More than just numbers. Irrigation and Drainage. 54:103–111

CAST (Council for Agricultural Science and Technology). (2006). Using Risk Analysis to Inform Microbial Food Safety Decisions. CAST Issue Paper 31. Ames, IA. June.

Castillo, A., Mercado, I., Lucia, L. M., Martínez-Ruiz, Y., Ponce de León, J., Murano, E. A., Acuff, G. R. 2004. *Salmonella* contamination during production of cantaloupe: a binational study. Journ. Food. Prot.71:2217-2222

CDC. 2008. Outbreak of *Salmonella* Serotype Saintpaul Infections Associated with Multiple Raw Produce Items —- United States. MMWR. 57;929-934

CDHS FDA. 2007. California Department of Health Services and US Food and Drug Administration. Investigation of an *Escherichia coli* O157:H7 outbreak associated with Dole pre-packaged spinach. 2007;1–50. Available from http://www.dhs.ca.gov/ps/fdb/html/food/envinvrpt.htm

Choi C, Song I, Stine S, Pimentel J, Gerba C. 2004.Role of irrigation and wastewater reuse: comparison of subsurface irrigation and furrow irrigation. Water Sci Technol 50: 61-68.

Cook, R.L. 2001. The U.S. Fresh Produce Industry: An Industry in Transition. Chapter 2 in *Postharvest Technology of Horticultural Crops*, Adel A. Kader (eds.), University of California Division of Agriculture and Natural Resources, Publication 3311 (2001): 5-30.

CSFSGLLGSC. 2006 updated July 2009. Commodity Specific Food Safety Guidelines for the Lettuce and Leafy Greens Supply Chain 1st ed. Accessible at http://www2.wga.com/DocumentLibrary/scienceandtech/LGMAAcceptedGAPs07.10.09.pdf

CSFSGLLGSC.2008. Commodity Specific Food Safety Guidelines for the Lettuce and Leafy Greens Supply Chain. Version 2 –Arizona. http://www.azlgma.gov/userfiles/Leafy%20Greens%20Guidance%20Arizona%20Clean%20082608.pdf

CSFSGFTSC. 2008. *Tomato Guidance* Document, 2nd Edition, *Commodity Specific* Food Safety Guidelines for the Fresh. *Tomato* Supply Chain. Accessible at http://www.unitedfresh.org/assets/files/Tomato%20Guidelines%20July08%20FINAL.pdf

CSG T-GAPs. 2006. Tomato Good Agricultural Practices (T-GAP) and Tomato Best Management Practices (T-BMP). http://www.floridatomatoes.org/FoodSafety/TOMATO_QA_on_T-GAP_and_T-BMP11-8-06.pdf

CSG Tomato. 2009. Food Safety Programs and Auditing Protocol for the Fresh Tomato Supply Chain http://www.unitedfresh.org/assets/tomato_metrics/Open_Field_Checklist.pdf

Dorner, S.M., Anderson, W., Slawson, R., Kouwen, N. and Peter M. Huck. 2006. Hydrologic Modeling of Pathogen Fate and Transport. Environ. Sci. Technol.40: 4746–4753

Doyle, M. and M. Erickson. 2007.Summer meeting 2007—the problems with fresh produce: an overview. J Appl Microbiol 105:317–330.

Duris, J.W., Haack, S.K. and L. R. Fogarty, 2009. Gene and Antigen Markers of Shiga-toxin Producing *E. coli* from Michigan and Indiana River Water: Occurrence and Relation to Recreational Water Quality Criteria. J Environ Qual. 38:1878-1886

FAO/WHO. 2009. Benefits and risks of the use of chlorine-containing disinfectants in food production and food processing: report of a joint FAO/WHO expert meeting, Ann Arbor, MI, USA, 27–30 May 2008.

Fan, X. et al. 2009. Microbial Safety of Fresh Produce. Eds. Blackwell-Wiley and IFT Press.

FDA (1998). "Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables." Federal Register, October 29, 1998 63(209): 58055-58056.

FDA. 2007. Food Protection Plan. [http://www.fda.gov/foodprotection/].

FDA. 2009. Proposed Commodity Specific Guidance Documents. Guide to Minimize Food Safety Hazards of Leafy Greens, Melons, and Tomatoes. http://www.fda.gov/Food/FoodSafety/Product-SpecificInformation/FruitsVegetablesJuices/FDAProduceSafetyActivities/ucm174086.htm

Ferguson, C., d. R. Husman, et al. (2003). "Fate and transport of surface water pathogens in watersheds." Crit. Rev. Environ. Sci. Ecol. 33: 299-361.

Gallegos-RoblesMA,Morales-LoredoA,Alvarez-OjedaG,VegaPA,Chew MY, Velarde S, and P. Fratamico. 2008. Identification of Salmonella serotypes isolated from cantaloupe and Chile pepper production systems in Mexico by PCR-restriction fragment length polymorphism. J Food Prot. 71:2217-2222.

Geldreich, E. E., and R. H. Bordner. 1971. Fecal contamination of fruits and vegetables during cultivation and processing for market - a review. *J Milk Food Technol* 34:184-195.

Gelting, R. 2007. Irrigation water issues potentially related to 2006 *E. coli* O157:H7 in spinach outbreak. CDC Addendum Report. Attachment 11: 24 pp.

Gerba, C. P. and J. E. J. Smith (2005). "Sources of pathogenic microorganisms and their fate during land application of wastes." J. Environ. Qual. 34: 42-48.

Gerba, C.P. 2009. The Role of Water and Water Testing in Produce Safety. Chapter 7 in Microbial Safety of Fresh Produce X. Fan et al. Eds. Blackwell-Wiley and IFT Press.

Guan, T. et al. 2001. Fate of foodborne bacterial pathogens in pesticide products. J. Sci. Food Agri. 81:503-512

Guan, T., Blank, G. and R.A. Holley. 2005. Survival of pathogenic bacteria in pesticide solutions and on treated tomato plants. Journal of Food Protection. 68:296-304.

Guo, X., van Iersel, M., Chen, J., Brackett, R., and Beuchat, L. 2002. Evidence of association of *Salmonellae* with tomato plants grown hydroponically in inoculated nutrient solution. Applied and Environmental Microbiology 68:3639-3643.

Hanning, I., Nutt, J.D. and S.C. Ricke. 2009. Salmonellosis outbreaks in the United States due to fresh

produce: Sources and potential intervention measures. Foodborne Pathogens and Disease. 69:635-648.

Harrington, J. 2009. Water for Agriculture: Global Change and Geographic Perspectives on Research Challenges for the Future. *Journal of Contemporary Water Research & Education* 142:36-41

Harris, L.J. 2008.Survival of attenuated *Escherichia coli* O157:H7 or surrogate in field-inoculated lettuce. California Lettuce Research Board 2008 Research Report. http://www.calgreens.org/

Harris, L.J. 2009.Survival of attenuated *Escherichia coli* O157:H7 or surrogate in field-inoculated lettuce. California Lettuce Research Board 2009 Research Report. http://www.calgreens.org/

Harwood, V. et al. 2005. Validity of the Indicator Organism Paradigm for Pathogen Reduction in Reclaimed Water and Public Health Protection. Appl Environ Microbiol. 71: 3163–3170.

Hillborn, E.D., Mermin, J.H., Mshar, P.A., Hadler, J.L., Voetsch, A.,Wojtkunski, C. et al. 1999. A multistate outbreak of *Escherichia coli* O157:H7 infections associated with consumption of mesclun lettuce. Arch. Intern. Med. 159: 1758–1764.

Ibekwe, A.M., Watt, P., Shouse, P. and C. M. Grieve. 2004. Fate of *Escherichia coli* O157:H7 in irrigation water on soils and plants as validated by culture method and real-time PCR. Can. J. Microbiol. 50: 1007-1014.

Ibekwe, A.M., P., Shouse, P. and C. M. Grieve. 2006. Quantification of survival of *Escherichia coli* O157:H7 on plants affected by contaminated irrigation water. *Eng. Life Sci.* 6:566–572.

Ibenyassine K, Mhand RA, Karamoko Y, Anajjar B, Chouibani MM, and M. Ennaji. 2007.Bacterial pathogens recovered from vegetables irrigated by wastewater in Morocco. *J Environ Health*. 69:47-51.

Ishii, S., T. Yan, et al. (2006). "Cladophora (Chlorophyta) spp. harbor human bacterial pathogens in nearshore water of Lake Michigan." Appl Environ Microbiol 72: 4545-53.

Islam, M., J. Morgan, M. P. Doyle, S. C. Phatak, P. Millner, and X. Jiang. 2004. Persistence of Salmonella enterica serovar typhimurium on lettuce and parsley and in soils on which they were grown in fields treated with contaminated manure composts or irrigation water. Foodborne Pathog Dis 1:27-35.

James, J. L., ed. 2006. *Microbial Hazard Identification of Fresh Fruit and Vegetables*. John Wiley and Sons, Inc., Hoboken, NJ.

Jiang, S. C. and W. Chu. 2004. PCR detection of pathogenic viruses in southern California urban rivers. J. Appl. Microbiol. 97:17-28.

Jiang, S. C., W. Chu, B. H. Olson, J. He, S. Choi, J. Zhang, J. Y. Le, P. B. Gedalanga. 2007. Microbial source tracking in a small southern California urban watershed indicates wild animals and growth as the source of fecal bacteria. *Applied Microbiology and Biotechnology* 76 (4): 927-934

Koike, S. T., Cahn, M. D., and Suslow, T. V. 2008. Survival of generic *E. coli* under different irrigation systems. California Leafy Greens Research Board. 2007-2008 Annual Report. http://www.calgreens.org/

Koike, S. T., Cahn, M. D., and Suslow, T. V. 2009. Survival and biology of *E. coli* under field production environments. California Leafy Greens Research Board. 2008-2009 Annual Report. http://www.calgreens.org/

Loge, F., Thompson, D. and D. R. Call. 2002.PCR Detection of Specific Pathogens in Water: A Risk-Based Analysis. *Environ. Sci. Technol*., 2002, 36:2754–2759

Lu, L., . Humea, M., Sternesc, K.L., and S. D. Pillaia, 2004. Genetic diversity of Escherichia coli isolates in irrigation water and associated sediments: implications for source tracking. Water Research. 38:3899–3908.

Maki, R. P., and R. E. Hicks. 2002. Salmonella typhimurium survival and viability is unaltered by suspended particles in freshwater. *J Environ Qual* 31:1702-1709.

Marr, B. 2001. Principles for Preparing Water Quality Objectives in British Columbia. Publication of the Ministry of Environment, Lands and Parks. Government of British Columbia, CN.

Morace,G. et al. . 2002. Microbial quality of wastewater: detection of hepatitis A virus by reverse transcriptase-polymerase chain reaction. Journal of Applied Microbiology. 92:828 - 836

Oron G, Armon R, Mandelbaum R, Manor Y, Campos C, Gillerman L, Salgot M, Gerba C, Klein I, Enriquez C. 2001. Secondary wastewater disposal for crop irrigation with minimal risks. Water Sci Technol 43: 139-146.

Pillai, S. D. and S.D. Pillai. 1998. Microbial Pathogens within Aquifers: Principles and Protocols. Springer Verlag. New York, NY. 163 pp.

Rai PK and Tripathi B.D. 2007. Microbial contamination in vegetables due to irrigation with partially treated municipal wastewater in a tropical city. *Int J Environ Health Res*. 17:389-395.

Ruiz, B. G. V., R. G. Vargas, and R. Garcia-Villanova. 1987. Contamination of fresh vegetables during cultivation and marketing. *Int J Food Microbiol* 4:285-291

Sadovski AY, Fattal B, Goldberg D, Katzenelson E, Shuval HI. 1978. High levels of microbial contamination of vegetables irrigated with wastewater by the drip method. Appl Environ Microbiol 36: 824-830.

Sapers, G. M., J. R. Gorny, and A. E. Yousef, eds. 2006. *Microbiology of Fruits and Vegetables*. CRC Taylor & Francis Group, Boca Raton.69.

Sherer, B., Miner, J., Moore, J., and J. Buckhouse. 1992. Indicator bacterial survival in stream sediments. Journal of Environmental Quality 21:591-595.

Sinclair RG, Romero-Gomez P, Choi CY, Gerba CP. 2009. Examination Of MS-2 Phage And Salt Tracers To Characterize Axial Dispersion In Water Distribution Systems. J Environ Sci Health. 10:963-971

Sivapalasingam, S., Barrett, E., Kimura, A., Van Duyne, S., Phan, W. W. Q., Gould,E, Shillam, P., Reddy, V., Cooper, T., Hoekstra, M., Higgins, C., Sanders, J., Tauxe, R., and Slutsker, L. 2003. A multistate outbreak of *Salmonella enterica* serotype Newport linked to mango consumption: Impact of water-dip disinfestation technology. Clinical Infectious Diseases 37:1585-1590.

Solomon, E.B., Yaron, S., and Matthews, K.R. 2002*a*. Transmission of *Escherichia coli* O157:H7 from contaminated manure and irrigation water to lettuce plant tissue and its subsequent internalization. Appl. Environ. Microbiol. 68: 397–400.

Solomon, E.B., Potenski, C.J., and Matthews, K.R. 2002*b*. Effects of irrigation methods on transmission to and persistence of *Escherichia coli* O157:H7 on lettuce. J. Food Prot. 65: 673–676.

Song, I., S. W. Stine, et al. (2006). “Comparison of crop contamination by microorganisms during subsurface drip and furrow irrigation.” J. Environ. Engin. 132: 1243-1248

Steele, M., and Odemeru, J. 2004. Irrigation water as a source of food-borne pathogens on fruits and vegetables. Journal of Food Protection 67:2839-2849.

Stine, S. W., I. Song, C. Y. Choi, and C. P. Gerba. 2005. Application of microbial risk assessment to the development of standards for enteric pathogens in water used to irrigate fresh produce. Journal of Food Protection 68:913-918.

Stine SW, Song I, Choi CY, Gerba CP. 2005b. Effect of relative humidity on preharvest survival of bacterial and viral pathogens on the surface of cantaloupe, lettuce, and bell peppers. J Food Protect 68: 1352-1358.

Suslow, T.V. 2002. Production practices affecting the potential for persistent contamination of plants by microbial foodborne pathogens. Chapter 16. In: Phyllosphere Microbiology. APS Press, Minneapolis, MN. pp. 241-256

Suslow, T.V., M.P. Oria, L.R. Beuchat, E.H. Garrett, M.E. Parish, L.J. Harris, J.N. Farber, F.F. Busta. 2003. Production practices as risk factors in microbial food safety of fresh and fresh-cut produce. Comprehensive Reviews in Food Science and Food Safety 2S:38-77.

Teplitski, M., Barak, J.D. and K. R Schneider. 2009.Human enteric pathogens in produce: un-answered ecological questions with direct implications for food safety. Current Opinion in Biotechnology. 20:166–171

Tyrell, S., Knox, J., and Weatherhead, E. 2006. Microbiological water quality requirements for salad irrigation in the United Kingdom. Journal of Food Protection 69:2029-2035

USDA NASS. 2009. 2007 Census of Agriculture. Specialty Crops Volume 2 Part 8. Accessible at www.nass.usda.gov

USDA NASS. 2008. Farm and Ranch Irrigation Survey. www.agcensus.usda.gov www.agcensus.usda.gov

USEPA (1973). *Water Quality Criteria*. National Academy of Sciences Report to the United States Environmental Protection Agency. USEPA, Washington DC, pp. 350–366.

USEPA. 1996. National water quality inventory, 1996 report to Congress. EPA 841-R 97-008. U.S. EPA, Washington, D.C.

Wang, G., and M. P. Doyle. 1998. Survival of enterohemorrhagic *Escherichia coli* O157:H7 in water. J. Food Prot. 61:662–667.

Wheeler, C., T. M. Vogt, G. L. Armstrong, G. Vaughan, A. Weltman, O. V. Nainan, V. Dato, G. Xia, K. Waller, J. Amon, T. M. Lee, A. Highbaugh-Battle, C. Hembree, S. Evenson, M. A. Ruta, I. T. Williams, A. E. Fiore, and B. P. Bell. 2005. An outbreak of hepatitis A associated with green onions. *N Engl J Med* 353:890-897.

WHO. 1989. Health Guidelines for the Use ofWastewater in Agriculture and Aquaculture. Report of a Scientific Group, Technical Report Series 778. World Health Organization: Geneva; 74 pp

Winfield, M. D., and E. A. Groisman. 2003. Role of Nonhost Environments in the Lifestyles of Salmonella and Escherichia coli, 69:3687-3694.