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Abstract: We evaluated the potential for human illness from a hypothetical recreational exposure to freshwater that was impacted by land-applied, agricultural animal fecal material. The scenario included 1) fresh cattle manure, pig slurry, or chicken litter (fecal material) land-applied, adjacent to a freshwater waterbody at standard agronomic rates (based on nutrient management); 2) fecal materials containing fecal indicator bacteria (FIB) and pathogens of public health concern (reference pathogens) at levels reported in peer-reviewed literature; 3) FIB and reference pathogens mobilized via runoff at rates estimated from our rainfall simulation experiments; 4) primary recreational contact (e.g., swimming) occurring in undiluted runoff at the edge of the waterbody or in diluted runoff containing specific reference levels of FIB in the waterbody; and 5) exposure to reference pathogens occurring through ingestion of water during recreation. We present quantitative microbial risk assessment (QMRA) model results based on this exposure scenario. We also compare results to our previously published work addressing direct contamination to freshwater. Finally, we discuss management considerations and implications for site-specific water quality criteria.

Keywords*:* Integrated Environmental Modeling; Watershed modeling; QMRA; Pathogens; FIB

1 INTRODUCTION

Managing and minimizing the public health threat associated with fecal pollution in recreational water are important aspects of policy development and regulation for the U.S. Environmental Protection Agency (EPA) Office of Water. Human exposure to recreational water impacted by fecal contamination is known to cause a variety of adverse health effects including gastrointestinal (GI), respiratory, skin, and eye illnesses (Craun et al., 2005; NRC, 2004; Parkhurst et al., 2007). Microbial hazards in recreational water contaminated by feces include pathogenic bacteria, viruses, and parasitic protozoa of human and animal origin. Risks to swimmers may differ depending on the source (human or animal) of the excreta because the (1) pathogens in animal manure differ in type, occurrence, and abundance from those in human sewage (Cotruvo et al., 2004); and (2) routes by which human-infectious pathogens of animal origin (zoonoses) reach swimmers can differ from human enteric pathogens (e.g., intermittent rainfall transport compared to wastewater treatment plant effluent with relatively constant flow).

This quantitative microbial risk assessment (QMRA) estimates human GI illness associated with recreation at a freshwater beach contaminated by fecal material from agricultural animal sources (livestock). It compares those risks to those associated with recreation in water impacted by human sewage sources. The assessment follows a standard microbial risk assessment framework and employs peer-reviewed microbial risk assessment tools and approaches (EPA, 2012b).

2 METHODS AND MATERIALS

Figure 1 illustrates conceptually the processes leading to human exposure to pathogens in freshwater impacted by fecal contamination from agricultural sources. We refer to this exposure scenario as indirect contamination since the fecal material is land applied, and then mobilizes to the recreational water via rainfall runoff. We conducted a literature review to characterize the parameters associated with these processes (EPA, 2012a; EPA, 2010).

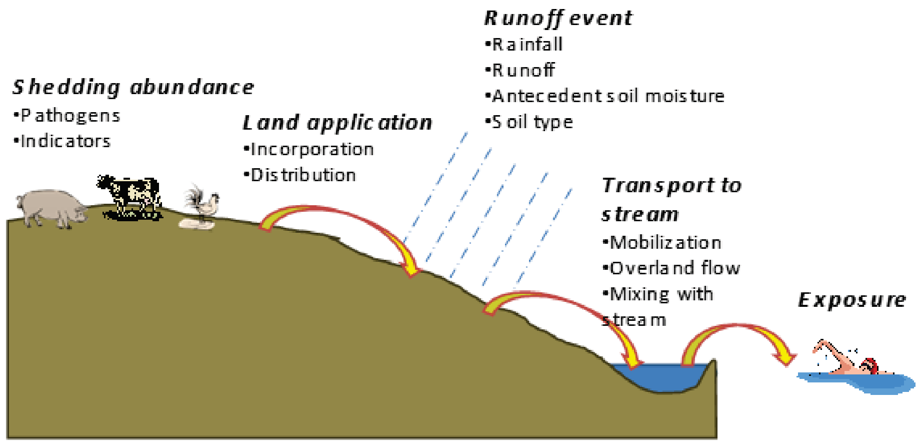

Figure 1. Schematic exposure diagram for hypothetical recreation at agricultural animal-impacted waterbody

We conducted an environmental monitoring and sampling study to characterize zoonotic enteric pathogens and FIB densities in surface water affected by agricultural activities (EPA, 2010). The study design emphasized overland transport inputs and processes. The monitoring regime/approach included rain simulation experiments in small plots amended with cattle manure, pig slurry from a lagoon, and un-composited litter from a chicken operation. These experiments are described under separate cover (EPA, 2010). This analysis encompasses the full set of four rainfall experiments, each approximately covering a different season.

The QMRA analyses were conducted using two complementary approaches as described previously by EPA (2010). First, the estimated risks were calculated for a hypothetical waterbody containing sufficient indirect contamination from each source so that the geometric mean FIB densities are at the 2012 RWQC-recommended FIB levels (35 CFU per 100 mL enterococci and 126 CFU per 100 mL *E. coli*, respectively) (referred to hereafter as the "Relative QMRA"). The results from this analysis can be compared to the direct contamination results reported by Soller et al. (2010) since the exposure scenarios are similar. For these analyses, we compared the relative risk of illness associated with recreation at a freshwater beach indirectly impacted (via rainfall runoff) by cattle, pig, or chicken sources of fecal contamination versus human sewage-impacted recreational water.

The reference pathogens for animal contamination included *Cryptosporidium* spp., *Giardia lamblia*, *Campylobacter jejuni*, *Salmonella enterica*, and *E. coli* O157:H7. The risk associated with each fecal contamination source was characterized as the total probability of GI illness using the probability of illness from each source-specific pathogen in a manner that is parallel to computing annual risks of infection by combining daily risks (Regli et al., 1991):

$$P_{ill}^{S} = 1 - \prod_{rp} (1 - P_{ill_{rp}}^{S})$$

This process was repeated 10,000 times for each fecal contamination source to generate a distribution of risk. For both sets of analyses, runoff is assumed to be from freshly-applied, untreated manures.

For the first set of analyses, the exposure model used in the relative QMRA simulations was similar to that employed by Schoen and Ashbolt (2010) and Soller et al. (2010) with the addition of a term accounting for relative differences in mobilization fraction among indicators and reference pathogens. For each reference pathogen, rp, and source material, S, the dose ingested by a swimmer in waters immediately downstream of the point of entry of runoff from the field is estimated as detailed below. Those doses were used as input to an exposure model in which a fraction of pathogens present in the applied wastes is assumed to mobilise in the runoff. The runoff was assumed to be undiluted in the recreational waters where exposure occurred. The mobilization fractions were drawn from the experimental data. The estimated dose was then used as input to the appropriate dose-response relationship resulting in a probability of infection, and subsequent illness, based on the reference pathogen morbidity factor.

$$\mu_{rp}^{S} = \frac{C_{FIB}}{\left(R_{FIB}^{S} \times f_{FIB}^{S}\right) \times 100} \times \left(f_{rp}^{S} \times R_{rp}^{S}\right) \times p_{rp}^{S} \times I_{rp}^{S} \times V_{I}$$

where

μ_{rp}^{S} is the ingested dose for reference pathogen *rp* originating from source *S* (# of organisms)

S is the fecal contamination source;

C_{FIB} is the waterbody density (i.e., reference density) of enterococci or *E. coli* (CFU or MPN 100 mL^{-1});

R_{FIB}^{S} is the density of FIB in land-applied manure (MPN/CFU g^{-1} or MPN/CFU mL^{-1});

f_{FIB}^{S} is the mobilization fraction of the FIB for the fecal source (# FIB/100 mL runoff) / (# FIB/g manure) or (# FIB/100 mL manure runoff / # FIB/mL manure slurry);

R_{rp}^{S} is the density of pathogen species in land-applied manures with pathogens (# rp g^{-1} for cattle and chicken wastes and # rp mL^{-1} for pig slurry)

f_{rp}^{S} is the mobilization fraction of the pathogen species for the fecal source (# rp/100 mL runoff) / (# rp/g manure) or (# rp/100 mL manure runoff / # rp/mL manure slurry);

p_{rp}^{S} is the fraction of human-infectious pathogenic strains from source S (dimensionless);

I_{rp}^{S} is the prevalence of infection in the non-human source (proportion of animals shedding the pathogen; dimensionless); and

V_I is the volume of water ingested (mL).

The factor of 100 is the unit conversion between the runoff volume in 100 mL and ingestion volume in mL.

In the second set of analyses, the risk associated with each fecal contamination source (cattle, pig, and chicken) was characterized as the estimated total probability of GI illness in the runoff-driven event, based on the probability of illness from each of the reference pathogens (referred to hereafter as the "Forward QMRA"). In these QMRA simulations for each of the livestock manures, the density of reference pathogens in the runoff was calculated as the product of the reference pathogen density in land applied fecal waste (obtained from the literature survey), prevalence (average proportion of animals that are shedding the reference pathogen at any point in time), human infectious potential of the pathogen, and proportion of the applied reference pathogens that ran-off following a rain event divided by volume of the runoff for the event. Then, the estimated dose was then used as input to the appropriate dose-response relationship resulting in a probability of infection, and subsequent illness, based on the reference pathogen morbidity factor.

3 RESULTS

Results from the relative QMRA indicate that the predicted median risk of illness from recreational exposure to the cattle-impacted waterbody is 30- to 180-times lower (at the recommended RWQC enterococci or *E. coli* geometric mean, respectively) than the benchmark level of illness associated with the 2012 RWQC. Furthermore, the indirect scenario cattle-associated illness estimates are over 100 times lower than the direct fecal deposition cattle scenario reported by Soller et al. (2010). The results also indicate that the predicted median risk of illness from recreational exposure to the pig-impacted waterbody is approximately 35 to 65 times lower and the chicken-impacted waterbody is approximately 25 to 6000 times lower (at the recommended RWQC enterococci or *E. coli* geometric mean, respectively) than the benchmark level of illness associated with the 2012 RWQC.

In the forward QMRA, the predicted median risk of illness from a recreational exposure to the undiluted runoff from each of the land-applied fecal materials was:

1. 46 illnesses per 1,000 recreation events with an associated geometric mean of 1.4×10^4 (14,000) CFU enterococci per 100mL from cattle manure runoff;
2. 15 illnesses per 1,000 recreation events with an associated geometric mean of 3.6×10^4 (36,000) CFU enterococci per 100mL from runoff containing pig feces; and
3. 18 illnesses per 1,000 recreation events with an associated geometric mean of 1.8×10^3 (1,800) CFU enterococci per 100mL from runoff containing chicken feces.

For each of these fecal sources, the potential human health effects were affected by the pathogen levels in the runoff, whereas the level of FIB typically signified the extent of fecal loading to a waterbody. For example, the median risk of illness from the forward QRMA, cattle scenario simulations was greater than the benchmark recommended by EPA; however, for perspective, the illness level occurred at highly elevated enterococci levels (e.g., 14,000 CFU per 100 mL). This corroborates the results of the relative QMRA, discussed above. A similar pattern was observed for the other two animal scenarios.

4 DISCUSSION

The analyses discussed here complement and extend those described previously (Soller et al., 2010; EPA, 2010a). In this study, rainfall-induced mobilization of microbes from land-applied fecal materials (indirect contamination) was evaluated. The analysis described by Soller et al. (2010) considered direct deposition of fecal contamination to the stream (direct contamination) and subsequent recreation in close proximity to the contamination. While this analysis does not include all of the fate and transport parameters one would expect in a ‘real world’ scenario, the strength of this analysis is the comparison of the source-specific risk estimates from the indirect (land-applied & mobilized to water) scenario to its counterpart direct contamination scenario. Such a comparison could be used as an additional tool to evaluate the effectiveness of various manure management practices.

In comparing the first set of analyses conducted for this study to those reported previously (Soller et al., 2010), potential benefits of including fate and transport characteristics within the QMRA framework become apparent. In this QMRA, the relative QMRA addresses the question of how much risk may occur from recreational exposure to indirect animal contamination if a waterbody barely meets the geometric mean FIB densities recommended in the 2012 RWQC. By selecting the RWQC geometric mean FIB levels as the comparison point, risks in human-impacted waters inherently serve as a reference because the RWQC provides an estimated level of public health protection in human-impacted water estimated from epidemiology studies (EPA, 2012a).

The forward QMRA addresses the question of what the risk would have been in undiluted runoff containing fecal material from each animal source. These analyses highlight that potential human health risks are a function of both the nature of the source (i.e., the feces originated from which animal) and the magnitude of the fecal loading, not just the level of a particular cultured FIB. Forward QMRA estimates based on the level of pathogens in the water and the exposure scenario investigated benefit from the FIB water quality information for context to facilitate a rational comparison to existing water quality standards. The geometric mean FIB densities observed in the runoff experiments were presented for that purpose. For example, in the chicken-impacted waterbody, the predicted median risk of illness for a recreational exposure was 18 illnesses per 1,000 recreation events with a geometric mean of 1,800 CFU enterococci per 100mL. While the estimated risks were similar to recommended benchmark risks (EPA, 2012a), that risk profile occurred at an elevated level of FIB. Taken together, the analyses reported here provide a robust understanding of indirect contamination compared to direct contamination from animal sources.

To provide context to these risk estimates, we compared these QMRA results to a summary of literature reports on recreational water outbreaks from animal-related sources (EPA, 2009). The outbreak literature indicates that the sources of fecal contamination and the pathogen source in the majority of recreational water-related outbreaks remain unknown. There are several examples, however, of recreational water outbreaks where cattle were the principal source of contamination (Cransberg et al., 1996; Feldman et al., 2002; Ihekweazu et al., 2006). In those outbreaks, *E. coli* O157 was the etiologic agent of primary concern which is consistent with the results of this QMRA. No outbreak reports are available for pig- or chicken-impacted waters.

5 SUMMARY

This QMRA extends the analyses reported by Soller et al. (2010) by considering indirect contamination (via runoff from land-applied agricultural animal fecal materials) compared to direct contamination. EPA (2010) conducted a series of field experiments using land-applied cattle manure, pig slurry and chicken litter and simulated rainfall regimes to characterize mobilization of FIB and pathogens in the study area. Here, we included the results from four mobilization experiments to modify the fecal-loading of FIB and pathogens parameters in the QMRA analysis discussed in EPA (2010). Assumptions included in this risk assessment were that: 1) fecal materials were applied at standard agronomic recommended rates; 2) levels of FIB and pathogens in the fecal materials were representative of the source; and, 3) simulated rainfall-induced mobilization of microbes from the study are representative of the natural physical process. The exposure profile assumed recreational exposure occurred in the undiluted runoff.

The results of the QMRA analysis predict similar or lower risks of illness from indirect loading of animal sources, compared to the direct loading scenario (Soller et al., 2010), at the FIB levels recommended in the 2012 RWQC (EPA, 2012a). The risks associated with indirect contamination are decreased for cattle and essentially unchanged for pig- and chicken-impacted water compared to the direct contamination scenario. Notably, cattle-associated risks from the indirect contamination scenario decreased over 100-fold compared to the direct deposition scenario. The pig- and chicken-associated risk estimates were low in the direct scenario and did not decrease further in the indirect scenario. Differences in potential risks between the direct and indirect cattle feces deposition scenarios can be attributed to the decreased direct mass loading of feces to a waterbody and the differential mobilization of FIB and reference pathogens from the applied fecal materials.

These results suggest that management practices preventing direct contamination for water quality management potentially depend on the source of the fecal contamination. Practices which reduce the mass loading of feces to waters reduce the potential for human illness resulting from recreational exposures by decreasing the magnitude of the fecal contamination and through differential fate and transport (i.e., mobilization) between FIB and pathogens from land-applied fecal materials. These analyses suggest that: 1) Indirect fecal contamination (via runoff) from land-applied agricultural animal fecal materials results in predicted illness levels that are similar to or lower than those associated with direct contamination; 2) Indirect cattle fecal contamination poses substantially less recreational health risks compared to the direct cattle deposition scenario; 3) Management practices that reduce direct fecal loadings to surface waters can be effective in decreasing health risks from recreational exposure to waters impacted by cattle feces; and 4) States may consider these results as a foundation for developing source-based recreational water quality standards for waters not predominantly impacted by WWTP effluents.

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