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Review

Development of a risk-based index for source water protection planning, which supports the reduction of pathogens from agricultural activity entering water resources

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Abstract

Source water protection planning (SWPP) is an approach to prevent contamination of ground and surface water in watersheds where these resources may be abstracted for drinking or used for recreation. For SWPP the hazards within a watershed that could contribute to water contamination are identified together with the pathways that link them to the water resource. In rural areas, farms are significant potential sources of pathogens. A risk-based index can be used to support the assessment of the potential for contamination following guidelines on safety and operational efficacy of processes and practices developed as beneficial approaches to agricultural land management. Evaluation of the health risk for a target population requires knowledge of the strength of the hazard with respect to the pathogen load (mass $\times$ concentration). Manure handling and on-site wastewater treatment systems form the most important hazards, and both can comprise confined and unconfined source elements. There is also a need to understand the modification of pathogen numbers (attenuation) together with characteristics of the established pathways (surface or subsurface), which allow the movement of the contaminant species from a source to a receptor (water source). Many practices for manure management have not been fully evaluated for their impact on pathogen survival and transport in the environment. A key component is the identification of potential pathways of contaminant transport. This requires the development of a suitable digital elevation model of the watershed for surface movement and information on local groundwater aquifer systems for subsurface flows. Both require detailed soils and geological information. The pathways to surface and groundwater resources can then be identified. Details of land management, farm management practices (including animal and manure management) and agronomic practices have to be obtained, possibly from questionnaires completed by each producer within the watershed. To confirm that potential pathways are active requires some microbial source tracking. One possibility is to identify the molecular types of *Escherichia coli* present in each hazard on a farm. An essential part of any such index is the identification of mitigation strategies and practices that can reduce the magnitude of the hazard or block open pathways.

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1. Introduction

Source water protection planning is an approach to prevent contamination of ground and surface water in watersheds. Contaminated potable and recreational waters pose a direct threat to human health. Indirect threats to

health arise where water is used to irrigate fresh market crops. Evaluation of the health risk from a water resource (Collins and Rutherford, 2004; Gale, 2005) requires knowledge of the strength (pathogen load) of the hazard, and understanding the modification of pathogen numbers (attenuation) together with characteristics of the transport pathways (surface or subsurface).

Animal production and feeding operations represent a significant potential source of pathogens (Center for Disease Control and Prevention, 1998; Duffy, 2003; Gessel et al., 2004; Gerba and Smith, 2005). Pathogens of greatest

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Table 1
Characteristics of diseases caused by pathogens that can originate from farm waste (based on CAST, 1994)

Pathogens	Disease severity	Fatality case rate (%)	No. of cells to cause illness
<i>E. coli</i> 0157:H7	Moderate–severe	2.0	$<10^3$ – 10^9 CFU
<i>Salmonella</i>	Mild–severe	0.1	1 – 10^9 CFU
<i>Campylobacter</i>	Mild–Moderate	0.05	500 CFU
<i>Cryptosporidium</i>	Moderate–severe		10–30 Oocysts
<i>Giardia</i>	Mild–Moderate		10 Cysts

concern are shed into the environment in great numbers, are highly infectious to humans and other animals at relatively small doses (Table 1), survive and remain infectious in the environment for a considerable time (Avery et al., 2005; Kearney et al., 1993; Hutchinson et al., 2004), tend to be resistant to water treatment (Erlandsen and Mayer, 1984) and thereby increase water treatment costs. Infectious, water-related diseases are a major cause of morbidity, with an estimated 1.6 million deaths worldwide (WHO, 2003). Contaminating species include the parasite *Cryptosporidium parvum*, viruses and bacterial pathogens. In May of 2000 the town of Walkerton, Ontario, experienced the largest waterborne disease outbreak in Canada. The town water system was contaminated with pathogens that originated in manure and resulted in 2300 cases of gastroenteritis and seven deaths (O'Connor, 2002). Despite a thorough judicial inquiry, the actual pathway between the possible microbial sources and the groundwater could not be confirmed. Pathogen die-off in soil is potentially huge (reduction $>10^{20}$) and therefore soil represents a major barrier that helps to protect water resources (Gale, 2005). However, soil processes can be compromised and there is a need to develop indicator frameworks that allow semi-quantitative risk assessments to be made for pathogens until information accrues that will permit a full quantitative analysis. An essential part of any index is the identification of mitigation strategies and practices that can reduce the magnitude of the hazard or block open pathways between source and water resource. This paper describes the sources of pathogen contamination that can exist on farms and the processes that help attenuate pathogens and protect water resources.

2. Agricultural sources of pathogens (hazards)

Sources of faecal contaminate are diverse, and include confined and distributed sources (Joel and Karns, 2000). Distributed or unconfined sources include faeces deposited by pastured animals and wildlife, together with recognised organic amendments, such as manure and sewage biosolids. Partially confined sources include animal feedlots, animal housing and manure storages, and on-site wastewater treatment systems (Wyer et al., 1996; Jones and

Obiri-Danso, 1999). Many sources are subject to some level of control depending on decisions of the farmer.

Pathogens in manure, septage and sewage biosolids include *Listeria*, *Campylobacter*, *Salmonella*, *Escherichia coli* (*E. coli*) O157:H7, *Cryptosporidium* and *Giardia* (Hinton and Bale, 1991; Mawdsley et al., 1995; Pell, 1997; Wallis et al., 1996). Animal manure may contain disease organisms that are particular to the animal group but can also contain zoonotic disease organisms. Organic wastes become contaminated with human disease organisms coming from wild animals or because of failure in the segregation of waste streams. A small concentration of disease organisms relative to the total number of microbes has resulted in the use of indicator organisms, which provides an early warning that human pathogens may also be present. The enteric bacterium, *E. coli*, represents a reasonably effective indicator of the microbial quality of municipal drinking water (Medema et al., 1997) and domestic rural wells (Raina et al., 1999). *E. coli* concentrations of 10^8 to 10^{10} cfu per gram dry weight of freshly excreted faeces are three or more orders of magnitude greater than the upper values reported for pathogenic species.

A number of factors, including health status, animal type, age, diet, stress level and season determine the pathogen shedding rate (Joel and Karns, 2000; Nicholson et al., 2005; Russell et al., 2000; Bach et al., 2005a). The number of animals carrying or shedding pathogens at any one time varies in and between herds. Antibiotic treatment can induce shedding of infective material in some organisms (e.g. *E. coli* O157:H7) (Gyles, 2000), while a change of diet and feed regimes can have the same effect (Russell et al., 2000). Animals carrying zoonoses, such as *E. coli* O157:H7 may be symptom-free, so producers may be unaware that a problem exists. Pathogen concentrations in faeces may be reduced by employing probiotics (Fuller, 1999), vaccine technology (Glass, 2004) or the use of bacteriophages specific to an individual species or strain (Raya et al., 2006).

2.1. Confined and semi-confined sources

Domestic wastewater in rural areas is often treated by septic or other on-site wastewater disposal systems (OSWDS). Cleaning water from milking parlours and food processing facilities may be handled in the same way. Contaminants are initially confined in a tank, which retains solids and allows primary digestion to take place, while water and soluble materials seep into the soil from a distribution system.

Many outbreaks of waterborne disease can be traced to improperly functioning or poorly positioned OSWDS (Hagedorn et al., 1981). The capacity of soil to absorb effluent water is an important property; too rapid a flow can allow significant numbers of pathogens to move to groundwater (Yates, 1985). OSWDS need appropriate soil characteristics, topography and horizontal distance

to water courses to be effective in minimizing contamination (Day, 2004). Critical design parameters therefore include the depth to the water table or to bedrock and permeability of the subsurface soil, with wet soils (or those subject to inundation) or steeply sloping sites enhancing the likelihood that open pathways for transport will be present.

Key potential sources of pathogens on farms are those associated with the management of animal manure. Manure management can directly control pathogen load and indirectly influence survival and transport of pathogens from the soil to water resources through modifying the microbial environment. Housing animals and poultry usually requires some temporary storage of manure within the barn, before transfer to longer-term storage in readiness for land application. Faeces from livestock in outside pens or corrals are only partly confined unless runoff water is collected.

Storage changes bacterial populations. A slurry store or solid manure heap is likely to consist of excreta of different ages and may even come from different barns. Rates of pathogen decline in manures can be affected by diet, which also determines both physical and chemical properties of faecal and storage conditions (Plachá et al., 2001). Nicholson et al. (2005) concluded that temperature, aeration, pH and dry matter content, determine pathogen declination rates during storage. However, many of these factors vary with management practices. *Cryptosporidium parvum* oocysts survived in stored slurry despite the high levels of ammonium (Fleming et al., 1997). *Giardia* appears to be sensitive to freezing, whereas survival of other pathogens is enhanced. Temperatures above 30 °C generally reduce survival times and few organisms appear to survive for long in dried manure (Table 2).

Cattle slurry and poultry excreta contain concentrations typically about ten times greater than in pig slurry (Nodar et al., 1990). Initially, populations of viable organisms decline abruptly (Nodar et al., 1992) although persistence of *E. coli* O157:H7 (Bach et al., 2005b) can be more than 30 days at 22–23 °C, and even longer at lower temperatures (Kudva et al., 1998). *E. coli* O157:H7 survived for 21 months in an outside manure pile stored under fluctuating

environmental conditions; survival was shorter in slurries and organisms were undetectable after 5 days incubation at 23 °C (Kudva et al., 1998).

Manure treatment on farms can be through composting, both in-vessel and in windrows, which requires that a temperature above 55 °C be maintained long enough to kill pathogens (St. Jean, 1997). Mechanical separation of coarse solids from slurry produces a material that can be stacked and composted, with liquid being treated independently. *Cryptosporidium* oocysts introduced to residual liquid separated from cattle slurry became non-viable after 4.1 days (Read and Svoboda, 1995). Anaerobic digesters are in use, where the temperature for the process is either at ambient, when bacteria are not killed, or at temperatures of at least 55 °C, when pathogens are killed. Survival of 10% of *E. coli* and *Campylobacter jejuni* (*C. jejuni*) for longer than 50 days (Kearney et al., 1993), and for bovine enterovirus, longer than 13 days (Monteith et al., 1996), occurred at temperatures below 40 °C. Lime treatment (addition of quick or slaked lime) to raise the pH to 12 for at least 2 h (Table 3) has also been used for septage.

Structural reliability of containers for manure or domestic wastewater needs to be included in the risk assessment. The majority of storage systems are open-topped, so they collect precipitation but allow free gaseous exchange. Poor maintenance and earthen storages can lead to groundwater pollution (Rowell et al., 1985;

Table 3

Effect of treatment on the survival of bacteria (based on Millner, P., Personal Communication, March 2003)

Treatment	Log reduction	Stress
Lagoon	1–3	Time
Constructed wetland	2–3	Time, filtration
Deep stack (composting)	1–?	NH ₃ , heat
Digestion – mesophilic	1–2	Time; heat
Digestion – thermophilic	5	
Composting	1–5	Heat, time
Air drying	1–2	Dessication
Heat drying	4–5	Heat, dessication
Pasteurization	5	Time, heat
Alkaline process	3–5	Heat, NH ₃

Table 2

Persistence of potentially pathogenic organisms in manure (based on Wang et al., 1996; Jiang et al., 2002; Bach et al., 2005a)

Organism	Persistence under experimental conditions (days)					
	Frozen	5 °C	30 °C	Liquid manure	Compost	Dried
<i>E. coli</i>	>100	>100	10	100	7	1
<i>Salmonella</i>	>150	150	28	75	14	7
<i>Campylobacter</i>	50	21	7	100	7	1
<i>Giardia</i>	<1	7	7	300	14	1
<i>Cryptosporidium</i>	>300	50	28	>300	28	1
<i>E. coli</i> O157:H7		~5 °C 70	~15 °C >226	~22 °C 231		

Barrington et al., 1991). Earthen storage, in areas with shallow bedrock, pervious soils, and shallow water tables endanger water supplies unless artificial liners are used (Barrington et al., 1991). Problems with liquid manure storage systems contributed 17% of 229 listed manure spills recorded in Ontario (Blackie, M. Personal Communication, December, 2000).

Storage volume is an important issue: 34 of 38 manure spills were associated with problems from stored manure in the Southwestern Region of Ontario between 1988 and 1999. Limited storage (e.g., <180 days) increases the risk of spreading during conditions that can lead to environmental contamination (Fleming and Fraser, 2000). Spillage around stores represents a further source of contamination (Rudolph, 2003).

2.2. Unconfined sources

Direct animal access to water bodies poses a clear risk of contamination (Gary et al., 1983), which can be lessened by providing alternative drinking points. Behaviour of livestock is also important (Duncan et al., 1998; Veira et al., 2003). Direct voiding of faeces into streams can increase survival rates (Davies et al., 1995) as rapid sorption onto bed sediment can occur (Whiteley, 1998). Nevertheless, bacterial concentrations of 10 mL^{-1} have been found 20 km downstream from a source of contamination (Feresu and Van Sickle, 1990). Access to streams also allows animals to disturb the sediment, causing the release of stored pathogens into the water.

The majority of contamination incidents of water courses in the Southwestern Region of Ontario between 1988 and 1999 were related to land application of manure (Blackie, M. Personal Communication, 2000). Liquid manure is transported from storage to the field via pipelines, tanker-trailers, or custom truck-spreaders. There are three main methods of applying manure and biosolids: broadcasting, irrigation, and injection. Application method is important for the potential movement of pathogens. Liquid manure is applied to the soil surface of arable land or injected below the soil surface. The latter reduces the likelihood of any pathogens becoming airborne during spreading. Broadcast application of liquid manure from a tanker has resulted in fewer than a third of the problems of surface water contamination encountered with the use of spray irrigation. Failure of equipment associated with the land application caused 27% of manure spills that resulted in contamination of water courses in the South Western Region of Ontario between 1988 and 1999 (Blackie, M. Personal Communication, December, 2000).

Solid manure is typically applied by surface spreading, which then requires a second tillage operation for incorporation. Crane et al. (1983) concluded that land application of organic waste can significantly increase bacteria contamination of surface water from runoff, especially if farmers do not follow wise management options and safety precautions. Results from the Ontario

Farm Groundwater Quality Survey indicated that farmstead drinking water wells were more likely to be contaminated where manure was spread (Goss et al., 1998; Rudolph et al., 1998).

Factors to consider in relation to timing of application include the risks from soil compaction, likelihood of runoff and nutrient loss. Limited manure storage on many farms means the common periods for application are the fall, winter, and spring. Spring application may be limited by soil wetness, while fall or winter applications tend to result in longer survival times. The likelihood of bacteria moving into water resources declines with time after manure application due to die off, which takes longer in manure applied in late fall, shortly before any freeze-up. Application as a side dressing for maize (*Zea mays* L.) (generally in mid-June, when soils are relatively dry and warm) results in the shortest period of survival. In the first day after applying liquid manure, more bacteria may be lost in overland flow from no-till land than from ploughed land, but the rate of decline in the concentration of bacteria in the runoff water can also be greater (King et al., 1994).

The most frequently reported route by which liquid manure can contaminate surface water courses is outflow from tile-drain systems (e.g., Fleming and Bradshaw, 1991, 1992a, b). After liquid manure application, bacteria move rapidly to the tile drains, particularly if soils are close to field capacity or after injection (Foran et al., 1993). Of the manure spreading events investigated by Dean and Foran (1991), 75% resulted in water quality impairment. It is difficult to determine an acceptable rate of liquid manure application, due to the numerous factors which influence the potential for contamination of watercourses (Foran et al., 1993). Routine inspection of tile drain outfalls during manure application could reduce adverse impacts on water quality. Pre-tillage of soil before spreading liquid manure can disrupt pore continuity and minimize the direct impacts on tile-drain quality (Fleming and Bradshaw, 1992b).

3. Persistence of pathogens in the environment

A number of factors influence the survival of pathogens following land application of manure: properties of the soil, availability of nutrients (including carbon) and interactions with soil biota (Abu-Ashour et al., 1994). These interactions include competition with and predation by indigenous soil micro- and meso-organisms. The application medium also affects the survival of bacteria. For example, Östling and Lindgren (1991) found that 20–40 times more indigenous *Bacillus* spores were present on manured crops than on un-manured crops, and these numbers remained constant with time to harvest. However, bacteria originating in the manure itself, such as *Clostridium*, some coliforms, and *E. coli*, all declined with time after manure application. Thelin and Gifford (1983) showed that when freshly voided manure was subject to rainfall simulation within 5 days, the concentration of

faecal coliform bacteria in runoff was in the order of 10^4 mL^{-1} , but this number declined to 400 mL^{-1} after 30 days.

Using four undisturbed 50 cm clay loam cores, Unc (2002) demonstrated that up to 80% of the bacteria applied with liquid swine manure was recovered in the drainage water. On the other hand a significant proportion of the faecal bacteria applied with the solid beef manure were retained within the manure matrix.

Once in surface water, the survival of *E. coli* (ETEC), *C. jejuni* and *Yersinia enterocolitica* is such that this can be a persistent venue for transmission between animals and humans (Terzieva and McFeters, 1991). However, the survival of pathogens in water and soil is very variable (Feachem et al., 1983) and differs between species. Among bacteria, many Gram positive organisms form resistant spores, whereas in Gram negative organisms the physiological adaptation to environmental stress may involve the reduction in cell size and metabolic rate (Roszak and Colwell, 1987). Some pathogenic bacteria can survive in a dormant state in soils and water but cannot be grown in conventional media (i.e. viable but non-culturable) (Byrd et al., 1991).

Soil parameters that modify survival of non-indigenous bacteria and viruses include soil pH, soil water content, organic matter content, soil texture, temperature, availability of nutrients, adsorption properties of the soil (Gerba et al., 1975; MacLean, 1983; Cools et al., 2001). Bacteria can survive longer in cold soils and fine textured soils (Fenlon et al., 2000). In cold soils ($< 5^\circ \text{C}$) *E. coli* can survive for up to 100 days. Survival of *Enterococcus* spp. was longer than that of *E. coli* at 5°C , while the opposite was true at 15°C and 25°C (Cools et al., 2001). However, these authors also reported that while *Enterococcus* spp. survived longer in loamy soils than sandy soils at 25°C , the reverse was true for *E. coli*. Gagliardi and Karns (2000) reported that *E. coli* O157:H7 was able to replicate in and migrate through cores of various soil types. Numbers of the pathogen in leachate correlated with ammonium and nitrate levels, and the numbers exceeded inoculum levels in all treatments (i.e. soil types, tilled and no till, and rainfall amounts) except in intact clay loam cores (Gagliardi and Karns, 2000). Survival of non-pathogenic *E. coli* exceeded 60 days at 25°C and 100 days at 4°C (Bogosian et al., 1996) and may be extended beyond that by residing within soil protozoa (Barker et al., 1999).

It is likely that at least part of the effect of soil texture is related to the water-holding capacity (Sadovski et al., 1978). Cools et al. (2001) found that the best survival of *E. coli* and *Enterococcus* spp. occurred in soils close to field capacity. Mubiru et al. (2000) showed that at the same gravimetric water content, the matric potential was lower in a silt loam with a clay content of 0.25 g g^{-1} than one with 0.12 g g^{-1} , and the survival times for *E. coli* and *E. coli* O157:H7 were also shorter. *Campylobacter* species appear to have somewhat shorter survival times than *E. coli*. *C. jejuni* survived in soil for at least ten days but this

number could double when the ambient temperature decreased to 6°C (Lindenstruth and Ward, 1948).

Sunlight reduces the survival of bacteria and viruses in soil directly through the effect of UV light and as a result of drying (Yeager and O'Brien, 1979; Sinton et al., 1999; Gerba and Bitton, 1984; Mubiru et al., 2000). *Campylobacter* remains viable in a range of environments at 4°C for up to 7 days (HMSO, 1993). Other environmental constraints include its inability to tolerate desiccation, low pH ($< \text{pH } 5$), exposure to O_2 and UV light (HMSO, 1993). About 100 days is the longest survival time reported for enteric viruses.

The survival potential of *E. coli* in the absence of water stress was shown to be at least 200 days and was not dependent on the initial concentration of *E. coli* in the applied manure (Unc and Goss, 2006a). Solid beef manure accelerated microbial activity immediately after application and increased the initial number of *E. coli*, but also shortened the survival length compared to liquid swine manure (Fig. 1). Solid manure led to decreased survival at all incubation temperatures considered including freezing. The impact of liquid manure on bacterial survival following freezing seems to vary with soil type (Fig. 2).

After 48 h, a population of *Salmonella*, introduced to soil containing earthworms, was reduced by a factor of four compared with *Salmonella* in a worm-free soil. Earthworms also caused a small reduction in the population of the indigenous soil bacteria. Free living protozoa, nematodes, and the soil bacterium *Bdellovibrio* are also predators of bacteria in the soil (Peterson and Ward, 1989). On average, 10% of faecal coliforms and faecal streptococci were still present in the soil 11 and 14 days respectively after application of pig manure (Chandler et al., 1981).

Fig. 1. Persistence of *E. coli* from manure after incorporation in soil (Redrawn from Unc and Goss, 2006a).

Fig. 2. Changes in numbers of *E. coli* ($\log_{10} 100 \text{ g}^{-1}$ soil) following freezing (values relative to bacteria concentration at the start of the experiment (data from Unc and Goss, 2006a)).

In surface waters, sunlight reduces the longevity of bacteria, whereas factors, such as turbidity that decrease the transmission of light tend to increase survival time (Aramini et al., 2000). *Campylobacter* survival rates in freshwater can be up to 4 months with survival greatest at 4 °C (Rollins and Colwell, 1986; Thomas et al., 1999). Survival time, however, is highly dependent upon strain type, previous growth conditions, water quality, and environmental conditions (Buswell et al., 1998, 1999).

4. Pathways between hazard locations and water resources

Pathways are the routes that can bring about the transfer of pathogens at a source to the receptor (watercourse). Identification of pathways are required to build process-based predictive tools or to design strategies to prevent the contamination of water sources. Overland flow is one of the principal mechanism by which faecal pathogens reach surface waters (Davies et al., 2004). Significant numbers of bacteria reach groundwater by infiltration through soil and any underlying rock strata (Joy et al., 1998).

Water is the primary agent determining the movement of contaminants. Where precipitation (rainfall or irrigation) exceeds infiltration rate, ponding can promote preferential flow. Other preferential flow routes that develop include cracking soils, root and earthworm channels (Goss et al., 1984). Freeze–thaw cycles may also result in fractures. The installation of tile drains also provides some continuous porosity between the soil surface and the drain. The soil pore characteristics determine the ability for rapid conduit between the field and the surface water body into which the tile drains discharge. For example, preferential flow through macropore allowed manure liquids to move into subsurface drains within an hour after application (Fleming and Bradshaw, 1991, 1992a, b).

Manure can affect the partitioning of water in the period immediately after land application, but the direction of the change depends on both the manure type and the soil type. In loamy and finer-textured soils, the application of dilute liquid manure can both encourage surface runoff and enhance preferential flow. Until solid manure has been incorporated, it acts as mulch and encourages infiltration rather than surface runoff (Unc and Goss, 2006b).

The overland flow pathway can be moderated by practices that reduce surface runoff from unconfined or partially confined pathogen sources. Distance and land slope between hazards and water source determine the pathway potential (Fraser et al., 1998; Stephenson and Street 1978). Vegetation, crop residues and soil clods can reduce significantly source water contamination by trapping bacteria (Collins and Rutherford, 2004), while bare soil increases overland flow and reduces re-deposition of pathogens (Davies et al., 2004). Vegetated buffer strips are most effective when they increase infiltration into the soil, and this also increases their efficiency of contaminant removal from surface runoff (Coyne et al., 1998).

The other hydraulic pathway along which pathogens move involves movement through the soil matrix or at least through the pore system. However, attenuation of pathogens through the processes of adsorption, filtration and absorption (Medema et al., 1997; Collins and Rutherford, 2004) is dependent on soil's physical and chemical properties and land management (Xin and Boll, 2003; McKay et al., 2002; Huysman and Verstraete, 1993; Smith et al., 1985). Pathogen movement is also affected by chemical and physical properties of the waste (Unc and Goss, 2004).

Most enteric pathogens reach the soil in the biosolid material that contained them. Bacterial retention and transport depend on the hydrophobic and hydrophilic interactions between the cell surface, soil mineral and organic surfaces and the soluble and suspended components in the soil solution. Factors influencing the effectiveness with which soils retain bacteria and viruses include cation concentrations, clays, soluble organic concentrations, pH, isoelectric point of the viruses, and general chemical composition of the soil. Investigations conducted by Unc (2002) on bacterial transport through soils following land application of liquid swine manure and sold beef manure indicate that initial retention of faecal bacteria in soils can be enhanced at high ionic strength of the suspending solution after land application of manure. Subsequent dilution of the soil solution by incoming rain or irrigation favours re-suspension of initially retained microbial cells. However, presence of biosolids colloidal matter cancelled some of the effects of the increased ionic strength, favouring particle transport through the vadose zone. Thus, despite the complexity of the interactions between bacterial cells soils and suspending solution, organic matter in the biosolids reduces the variability in the retention behaviour given by the intrinsic properties of charged particles (i.e. bacterial cells). Initially charged particles are therefore more likely to remain in suspension

and penetrate deeper into the soil profile in the presence of suspended organic matter than they otherwise would.

5. Structure of the risk indicator

The risk of contaminating drinking water from a resource within an agricultural watershed depends on the number and size of pathogen sources, the existence of an active transport pathway, and any attenuation that occurs along the pathway (Fig. 3). The first component of an index of risk from pathogens is the identification, locating and sizing of each potential hazard. This requires the establishment of an inventory of confined and diffuse sources that exist on each farm in the watershed. Principally, this requires obtaining the locations and size of manure storages and OSWDS. Such information may be available from aerial photographs or satellite imagery, and the necessary validation of the interpretation is all the new material that would be necessary. Because of the influence of animal species, age, and management on the shedding of pathogens, the pathogen load in each hazard needs to be determined as a function of animal type, numbers and demography. In some jurisdictions, the required information on animals is available from census returns; in others it will need to be collected through questionnaires sent to producers. Basic information on animal and land management practices may well be obtained through the same mechanisms.

The second component is a compilation of information of die-off and growth rates for the different pathogen species in the different locations and media within potential pathways of movement. The boundaries between locations

and media are potential barriers to further movement. The attenuation in pathogen numbers across these boundaries needs also to be compiled. In combination, these data sets permit the reduction in the strength of the threat over time to be calculated for each pathogen at each location in the farm environment as they move from the point of excretion into defined pathways and reach the different barriers in the farm system. The barriers that need to be identified along the pathogen migration pathway include the delay between excretion and entry into temporary and longer-term storage, length of storage and treatment, conditions after land application and barriers during transport by infiltration or overland flow from a manure source and from a septic system source. A survey of farm management practices would help quantify the factors that influence the duration of passage along identified pathways. A climatic assessment tool is needed to identify the likelihood of significant transport events.

The third component is the identification of potential pathways from each source to the key water resources. Surface pathways could be identified using an established digital elevation model of the catchment together with soil and geological maps. The outcomes are locations of surface flows that intersect with surface water courses as well as those that lead to receiving locations, which form recharge foci for groundwater. To determine which pathways are active requires the implementation of a microbial source tracking protocol (Goss and Dunfield, 2004). Essentially, this likely requires molecular techniques to establish that microbes in the target water resource are of the same type as those present in any of the principal hazards on a given farm. Ideally, the same organism should be identifiable at an intermediate point along the pathway.

Fig. 3. Schematic drawing of the components of the pathogen risk index. Arrows below the framework indicate farmer decisions. Arrows within the framework indicate potential pathways for pathogen movement.

6. Conclusions

The development of a risk-based index of the potential for pathogens from agricultural activity to impact source waters is required as an interim stage in the establishment of a fully quantitative microbial risk assessment approach to source water protection. Based on the incidence of manure spills, unconfined sources are far more likely to pose threats to water resources, but the failure of confined sources can deliver very large loadings. There are significant limitations to identify and quantify the robustness of different barriers in attenuating the movement of pathogens. Particular emphasis needs to be put on the monitoring of subsurface drainage outfalls, as these can provide a direct link between preferential flow paths in the soil with surface waters.

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