Overland flow transport of pathogens from agricultural land receiving faecal wastes

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1. SUMMARY

Considerable investment has been made in recent years in improvements to the microbiological quality of urban wastewater discharges to surface waters, particularly in coastal towns, with the aim of reducing the exposure of bathers and surfers to gastrointestinal pathogens. As this source of pollution has come under greater control, attention has started to focus on diffuse catchment sources of faecal contamination which have been shown to be dominant during high river flows associated with storm events. This association with storm events suggests that rapidly responding hydrological pathways such as overland flow are likely to be important. The aim of this paper is to establish the current state of knowledge of pathogen transport processes in overland flow. In addition, the paper will attempt to convey the way that soil erosion science may aid our understanding of this environmental problem. The scale and nature of faecal waste applications to land in the UK is briefly reviewed, with data presented on both livestock slurry and manure, and human sewage sludge. Particular emphasis is placed on factors influencing the likelihood of pathogens making their way from infected livestock and humans to the soil surface, and therefore the chances of them being available for transport by overland flow. The literature relating to pathogen transport in overland flow is reviewed. Existing pathogen transport models treat pathogens as particles and link pathogen transport models to pathogen die-off kinetics. Such models do not attempt to describe the interactions that may occur between pathogens and soil and waste particles. Although conceptual models describing the possible states in which pathogen transport may occur have been proposed, an understanding of the factors controlling the partitioning of the microorganisms between the different states is only just beginning to emerge. The apparent poor performance of overland flow mitigation measures such as grass buffer strips in controlling the movement of faecal indicators highlights the need for a better understanding the dynamics of microbial transport so that better management approaches may be developed. Examples of on-going research into overland flow transport processes are briefly described and gaps in knowledge identified.

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2. INTRODUCTION

The introduction of the EC Bathing Waters Directive (76/160/EEC) [Council of the European Communities (CEC) 1976] focused attention on the causes on faecal contamination of natural waters. Discharges of untreated or partially treated urban wastewater from coastal towns into the sea were initially thought to be the principal cause of failure to meet the microbiological standards set out in the directive to protect the health of recreational water users at designated bathing sites. However, a series of studies (Wyer *et al.* 1996, 1998; Kay *et al.* 1999; Baudart *et al.* 2000) have demonstrated that whereas urban wastewater dominates faecal loads to bathing waters during low flow conditions, catchment sources of faecal pollution become the dominant input following rainfall events. These catchment sources of faecal pollution may include sewage sludge and livestock wastes applied to land; animal faeces deposited on land by grazing animals; discharges from septic tank systems; and defaecation by indigenous fauna (Wyer *et al.* 1994, 1996; Geldreich 1996; Jones and Obiri-Danso 1999; Obiri-Danso and Jones 1999). The observed link between rainfall, channel flow conditions and the dominance of diffuse sources of faecal pollution in catchment budgets suggests a key role for hydrological pathways that respond rapidly to storm events. One such pathway is overland flow. Overland flow occurs when rainfall is unable to infiltrate the soil surface and runs over the ground, normally in rivulets. Overland flow is of considerable interest to researchers studying diffuse pollution because it is the predominant means by which soil particles are transported from land to surface waters. The transport of soil particles can have deleterious effects on water quality such as bed siltation and increased turbidity. Furthermore, much has been learned in recent years of the potential for pollutants with a propensity for adsorption to soil particles (such as pesticides and phosphate) to be transported to watercourses in overland flow. It has also been recognized that faecal indicator bacteria and associated pathogens may be transported in overland flow (Van Donsel *et al.* 1967; McCaskey *et al.* 1971; Doran and Linn 1979; Khaleel *et al.* 1980; Crane *et al.* 1983; Patni *et al.* 1985; Mawdsley *et al.* 1995; Tate *et al.* 2000) and that this may be a significant cause of surface water contamination. Given the potential impacts of surface water contamination by faecal pathogens, understanding the processes by which microorganisms are transported from soils to waters is important if we wish to build process-based predictive tools or to design strategies to prevent the bacterial contamination of surface waters. The aim of this paper is to establish the current state of knowledge of pathogen transport processes in overland flow. The review will describe in general terms, the approaches commonly used in the study of soil erosion processes are being applied to this environmental microbiology problem.

3. FAECAL PATHOGENS IN SOILS

3.1 Sources

Large amounts of animal faecal wastes are applied to agricultural land in the UK. Nicholson *et al.* (2000) estimate that approximately 68 million tonnes (wet weight) were produced by housed livestock in 1997 in England and Wales, most of which is recycled back to agricultural land because of its fertilizer value. Approximately three-quarters of these wastes are produced by cattle and the remainder by sheep, pigs and poultry. Some 41% of faecal wastes will be in the form of either slurry (including dirty water) and 59% as farm yard manure (FYM). About 15% of grassland and 3% of tillage land receives slurry in any 1 year in England and Wales (Nicholson *et al.* 2000). Livestock faecal wastes may contain pathogenic microorganisms such as *Listeria*, *Campylobacter*, *Salmonella*, *Escherichia coli* 0157, *Cryptosporidium* and *Giardia* (Hinton and Bale 1991; Mawdsley *et al.* 1995; Pell 1997; Nicholson *et al.* 2000). Nicholson *et al.* (2000) in their review of risks of pathogen transfer into the food chain from manure applications to land state that there is a lack of data on 'typical' levels of pathogens in animal manures. Examples of reported incidence of key zoonotic pathogens in the faeces of cattle are presented in Table 1.

Prevalence of infection is only one of the factors influencing likelihood of pathogens being available at the soil surface for transport by overland flow. The actual numbers of pathogens shed is important and this has been found to be affected by a number of factors such as animal age, diet, stress and season (Nicholson *et al.* 2000). The probability of pathogens being available for transport at the soil surface is also likely to be influenced significantly by the duration and conditions of storage prior to land spreading. Although the Code of Good Agricultural Practice for the Protection of Water (MAFF 1998) recommends that a storage tank should hold at least 4-month slurry, in practice storage periods may be significantly less than that recommended as stores built before 1991 are usually exempt from the regulations. The environmental conditions that have been found to most significantly affect pathogen survival in storage have been identified in the review by Nicholson *et al.* (2000). This review concluded that temperature is the single most important factor which determines pathogen survival times in livestock manures. Other factors found to affect pathogen survival include ammonia, high pH, desiccation and competition. The method of waste storage will determine these conditions. For example, faecal wastes that have been subject to the manuring process are less likely to have high pathogen loads because of the combination of relatively high temperatures and long storage periods associated with this low-rate composting process. Recent trials in the UK have demonstrated that whilst pathogens could survive for up to

Table 1 Examples of reported incidence of key zoonotic pathogens in the faeces of cattle

Pathogen	Incidence in faecal samples (%)	Reference
Campylobacter spp.	89	Stanley *et al.* (1998)
Listeria monocytogenes	16	Pell (1997)
E. coli O157	1–5	Zhao *et al.* (1995)
	1–15	Jones (1999)
Salmonella spp.	23	Troutt *et al.* (2001)
Cryptosporidium spp.	48	Sturdee *et al.* (1998)

3 months in batched stored dairy slurry, they could not be detected after 1 week in an unturned manure heap (Nicholson *et al.* 2002).

The need to treat urban wastewater to high standards prior to discharge into receiving waters results in the production of a residue known as sewage sludge, and this requires disposal. Forecasts suggest that by 2005, the annual production of sludge (dry solids) in the UK will be approximately 1·5 million tonnes in the UK and 8·3 million tonnes in the Europe as a whole. It is forecast that by 2005, 71% of this sludge will be recycled to agricultural land in the UK (CEC 1999). The type and number of human pathogens present in untreated sewage sludge will vary according the prevalence of gastrointestinal disease in the community that produces it (Smith 1996). Sewage sludge is probably a less-important source of pathogen contamination of soil than livestock slurry and manure, however, because of the increasingly stringent operational restrictions on its use in agriculture. For example, in the UK the Sludge (Use in Agriculture) Regulations [Statutory Instrument (SI) UK 1989] which implement the Europe Sludge Directive 86/278/EEC (CEC 1986) require that only sludges that have been subjected to a recognized effective treatment process such as storage for 3 months may be applied to agricultural land. More recently, the Safe Sludge Matrix (http://www.adas.co.uk/matrix/) – an agreement between the water industry, food retailers and Government – will further reduce the chances of sludge pathogens being available for transport by overland flow. Key components of the Matrix include a phasing out of untreated sewage sludge use on agricultural land; restrictions on the use of conventionally treated sludges on risky crop groups such as salads, fruit and vegetables; and the requirement for enhanced treatment for the aforementioned risky crop groups. Enhanced treated sludge should be free from salmonellas (in five replicates of 2 g dried solids) and virtually free of other pathogens (as indicated by a 6 log reduction in the number of *E. coli*).

It should be noted that human or livestock faecal wastes are not the only potential source of transportable pathogens at the soil surface. Doran and Linn (1979) reported faecal coliform concentrations in runoff from ungrazed grassland in the range 150–50 000 CFU 100 ml^{-1}. Patni *et al.* (1985) report similar findings and concluded that the faeces of wild animals were probably the source of this contamination.

3.2 Survival in soil

The other major factor influencing the availability of waste-derived pathogens for overland flow transport is their survival in the soil environment. The survival in soil of pathogens originating from animal manures and sewage sludge has been reviewed by Van Donsel *et al.* (1967), Sorber and Moore (1987), Smith (1996) and Nicholson *et al.* (2000). Although a number of environmental factors have been shown to influence the survival of microorganisms in soil (e.g. temperature, moisture content, sunlight, pH and the availability of organic matter) these reviewers appear to agree that temperature is the most significant. In general, survival time increases with decreasing temperature. Nicholson *et al.* (2000) conclude that the majority of pathogens in manures applied to land will decline below detectable limits after 3 months. Therefore more pathogens are likely to be transported to a watercourse if an overland flow event occurs soon after faecal waste is applied to land.

The way that faecal wastes are applied to the land may also have a bearing on the survival and hence the chances of pathogen transport to watercourses. Intuitively, we would expect that faecal wastes spread onto the soil or crop surface are more likely to be subject to detachment and transport than wastes that have been injected below the soil surface or incorporated in some way. Walker *et al.* (1990) in their modelling work assume that only 50% of microorganisms are available if manures are incorporated to a depth of 10 cm. On the other hand, the environment at the soil surface may be more hostile because of the effects of insolation (e.g. u.v. irradiation, heating and desiccation) than the environment at depth. There is relatively little evidence in the literature of studies that have addressed the question of whether or not incorporation or injection will reduce pathogen losses. In a comparative study of runoff of faecal microorganisms and nutrients from grass plots that had received either injected or surface-applied slurry Heinonen-Tanski and Uusi-Kämppä (2001) concluded that there was no clear difference between application methods. Daniel *et al.* (1995) found no significant difference in runoff quality (no microbial indicators measured) between surface-applied and incorporated manure. Small scale rainfall simulation experiments conducted by the authors however suggest that there is approximately a 10-fold increase in faecal coliform transport if waste is surface-applied rather than incorporated (unpublished data).

4. OVERLAND FLOW TRANSPORT OF MICROORGANISMS

4.1 Empirical transport models

Most authors assume that microorganisms behave like soil particles, making predictions of pathogen transport using existing soil erosion models linked to models describing the die-off of microorganisms contained in animal wastes and manures before and after application to the soil. Once the population in the soil is predicted, it is assumed that the concentration can be multiplied by the soil loss to yield the number of microorganisms transported. This approach was used by Walker *et al.* (1990) who used the Modified

Universal Soil Loss Equation, an empirically based soil erosion model, to predict faecal coliform transport from soils amended with manures in the Owl Run catchment in Virginia, USA. To calculate the sediment yield for a single storm the model uses a number of empirically derived factors based on soils and topography combined with predicted peak and total runoff. The number of bacteria transported is calculated by assuming that a constant number of cells is transported with each unit mass of manure. To calculate the mass of manure eroded, empirical constants from the work of Khaleel *et al.* (1979) were used. The predicted range of faecal coliform concentrations was in the range of approximately 1000–2500 CFU 100 ml^{-1}. Unfortunately, no comparison was made with observed data.

Other recent attempts at predicting faecal coliform numbers transported in overland flow have focused on their transport through catchments. For example, Tian *et al.* (2002) describe the transport of *E. coli* as a function of surface runoff volume and an empirical delivery ratio based upon landscape factors; whereas Fraser *et al.* (1998) use a largely conceptual model to calculate a loading rate of faecal coliforms to streams. The model of Tian *et al.* (2002) was tested against data from the Mangatoama study site, a 1·45 km^2 predominately grazed catchment at the Whatawhata Research Centre, Hamilton, New Zealand. They found that predicted and measured *E. coli* counts were typically between 200 and 1300 CFU 100 ml^{-1}, however, on one occasion the sampled data were three times that of the model output. Fraser *et al.* (1998) found that their model was useful in being able to rank the relative risk of faecal contamination from livestock in 12 watersheds in New York State, ranging in size from 1·5 to 50 km^2. However correlation of predicted and observed faecal coliform concentrations in river water (mean measured values in the range 142 to 1657 CFU 100 ml^{-1}) proved non-significant.

Such methods allow us to make predictions of pathogen numbers transported to watercourses in overland flow, but do not relate to the processes acting on pathogens at the soil surface or after their entrainment in overland flow. In fact, there is only a limited experimental basis for describing these processes, but soil erosion science does at least offer a framework for investigating them further.

4.2 Pathogen transport processes

4.2.1 Initial and boundary conditions. Before the detachment and transport of microorganisms can be discussed, the initial and boundary conditions of the slurry-amended soil needs to be described. Previous workers (Reddy *et al.* 1981; Yeghiazarian and Montemagno 2000) have attempted to describe how the relationship between waste-derived microorganisms and soil and waste particles. Figure 1 illustrates three possible states in which microorganisms are likely to exist in a soil–slurry mixture, i.e.:

- attached to soil particles;
- attached to waste or slurry particles; and
- as unattached cells or clumps.

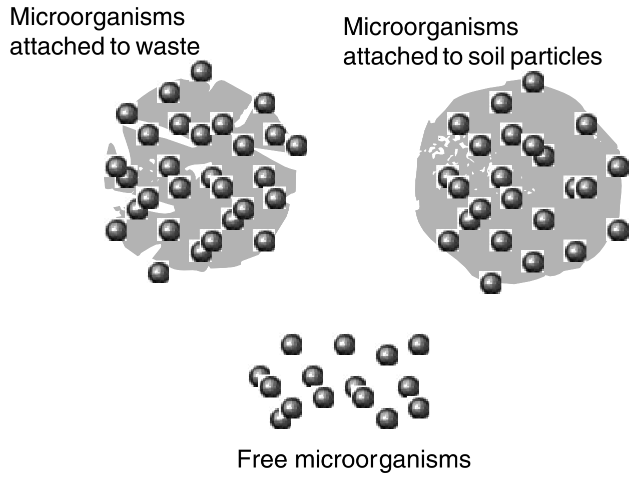

Fig. 1 Three likely states in which microorganisms are likely to exist in a soil–slurry mixture

A description of the factors controlling the partitioning of microorganisms between these different states does not presently exist. It is also recognized that there may be significant differences in partitioning associated with different microbial groups, e.g. bacteria and protozoa.

4.2.2 Initiation of overland flow. Overland flow occurs either when the rainfall intensity exceeds the soil's infiltration rate (infiltration excess overland flow); or when the soil become saturated with water so that no further rainfall can enter the soil (known as saturated overland flow). Once overland flow has been generated, by whichever mechanism, there is the potential for the rapid transport of microorganisms to surface waters.

4.2.3 Entrainment of microorganisms in overland flow. Soil erosion scientists classically divide soil erosion processes into three phases: detachment, transport and deposition (Meyer and Wischmeier 1969). These phases can occur as a result of the action of raindrops or the action of flowing water or a combination of both. We can assume that microorganisms positioned on the soil surface have the same processes acting upon them as a soil particle.

The detachment of microorganisms by raindrops or overland flow appears to have received very little attention. However, we suggest that microbial detachment will depend upon the properties of the microbial population and the properties of the detaching agent. We would suggest that the factors likely to affect the rate at which microorganisms are detached may include the number of microorganisms on the soil surface; whether or not they are protected by soil or biological material; how strongly they are adhered to particle surfaces and to each other; the kinetic energy of the rainfall; and the overland flow velocity and depth.

By combining Meyer and Wischmeier's (1969) model with the initial conditions as set out in Fig. 1 we can propose three potential pathogen transport scenarios. Figure 2a shows microorganisms as free cells within soil pore water or water films on the soil surface. They are incorporated into the flow as it passes over them. Those microorganisms which are attached to soil or waste particles are entrained when the force applied by the flow on the soil surface exceeds the soil and waste particles' resistance, or when they are hit by rain drops which may propel them into the flow (Fig. 2b). We expect that waste particles will have less resistance to these entrainment processes as they would typically be of lower density and only weakly consolidated. For phosphorus, Quinton *et al.* (2001) demonstrated that erosion processes were selective with proportionally more fine, phosphorus-containing material being moved in small runoff events. We can hypothesize that selective detachment and transport of waste particles and associated microorganisms is also likely to occur because of their low density when compared with soil mineral particles of the same size. The third scenario is where cells are detached from soil or waste particle surfaces by either raindrop impact or the flow itself and transported as free cells (Fig. 2c). Given these processes, the overland flow will contain a mix of microorganisms in the three states identified in Fig. 2 and, as with microorganisms in the soil (Fig. 1), we know virtually nothing about how microorganisms may be partitioned between these states whilst in transport.

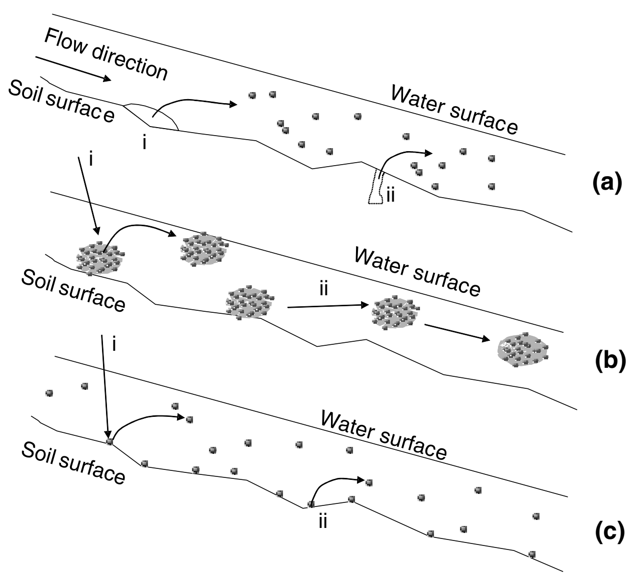

Fig. 2 Proposed pathogen transport scenarios: (a) shows the incorporation of free microorganisms in soil pores (i) and water films (ii) into overland flow; (b) shows the entrainment of waste or soil particles into overland flow as a result of raindrop (i) or flow (ii) detachment; (c) shows the detachment of microorganisms from soil surfaces as a result of raindrop (i) or flow (ii) detachment

4.2.4 Transport and deposition. It is well established the density and size of particles influences their settling velocity. Small, low-density particles settle more slowly than those of large, high density. For example, the low density of microorganisms, approximately 1·1 g cm^{-3} (Paul and Clark 1996) and their small size (typically 1–2 μm), suggests that once entrained they will remain in suspension. Similarly, it would be expected that a bacterial cell that is strongly adhered to a soil particle will not travel as far as one that is floating freely in suspension. Therefore, to model the deposition of microorganisms, it will be necessary to decide on the proportion of microorganisms moving freely and attached to particles, and how environmental factors, such as flow conditions and soil conditions will influence these proportions.

There is little evidence in the literature to support or refute these simple hypotheses. Most studies have been carried out in the field and have focused on the effectiveness of particular control measures. Those measures designed to trap microorganisms once entrained, such as vegetative filter strips (VFS), have been shown to be highly variable in their effectiveness. Coyne *et al.* (1998) show that between 55 and 95% of faecal coliforms and between 42 and 93% of faecal streptococci are trapped by the VFS. These figures compare with a much narrower range for sediment (95–99%). These figures are of the same order as those reported by Hayes *et al.* (1984) for sediment and Young *et al.* (1980) for faecal coliforms. The lower bacterial trapping efficiencies of the VFS support the argument that because of their lower density, deposition is less likely for free-floating microorganisms once entrained than it would be for a soil particle of similar size. If we assume that bacterial cells transported freely move with the water and are not deposited, unless all the water infiltrates, then we can also postulate that the observed reduction in microorganism numbers is due to the deposition of microorganisms associated with soil material. If this is the case, then the variability in trapping efficiencies reported by Coyne *et al.* (1998) may suggest variation in the partitioning of microorganisms between water and suspended sediment particles.

5. CONCLUSIONS

There is evidence to suggest that faecal pollution of watercourses from diffuse catchment sources occurs following storm events. This association with storm events suggests that rapidly responding hydrological pathways such as overland flow are likely to be important. Empirically based soil erosion models have been developed to predict pathogen loads associated with overland flow transport. These models are not intended to inform our understanding of the transport processes themselves. Pathogen transport is likely to be influenced by the initial conditions in slurry-amended soil, i.e. the relationship between faecal micro-organisms and soil and waste particles. A simple conceptual description of these initial conditions is suggested in this paper, but the fact remains that little has been published to date on this subject. Using well-established soil erosion process understanding we have attempted to describe the mechanisms which would facilitate pathogen transport in overland flow. Once again, there are only a relatively small number of studies with which to test our hypotheses. Further research is needed to properly test these hypotheses. A better understanding the dynamics of microbial transport will enable the development of better diffuse pollution management approaches.

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