3.2.4.4 *Summary*

Liquid manure can be stored in earthen lagoons or concrete storage facilities. Many of the latter are open-topped. Solid manure may be stored on concrete pads or in the open.

There is good evidence that if liquid manure stores leak, unless they are located in very coarse material, the solids in the manure effect a self-sealing and greatly limit the likelihood of groundwater contamination. Nonetheless, care must be taken to prevent drying out of the banks or bottoms of earthen lagoons so that shrinkage cracks do not form and allow obvious leak points to develop. During construction of concrete storages, care must be taken to ensure that any potential leak cannot intersect an open tile drain and thereby be diverted into a surface water source. There has been considerable concern over the integrity of concrete storages for liquid manure, but the evidence suggests that this is not a widespread problem in Ontario. Engineering solutions exist to deal with leakage from pipes that connect the barn with the storage.

Nitrogen is lost in gaseous form from manure storage. Ammonia escaping in this way can be deposited in surface water resources. Other gases contribute to the greenhouse gas effect. These losses not only reduce the nutrient value of manure to the producer, but losses from solid manure take place preferentially from the surface layers so that there is considerable variability in concentration with depth in the pile. This variability is not easily rectified since mixing solid manure before spreading is not readily achieved. Variability of nutrients with depth occurs in liquid manure, but mixing before spreading is relatively easy.

Bacterial populations can change significantly during storage. Their survival rates differ, depending on whether the manure is anaerobic or aerobic. Temperature also affects survival rate of pathogens, but not always in the same direction. Survival of *E. coli* O157:H7 is enhanced by cooler temperatures.

The concentration of metals tends to increase during storage because of the loss of organic matter.

3.2.5 Processing and treatment

There may be some risk to water resources from the processing or treatment of manure on farms. The microorganism content may also change during treatment. However, the main change is in nutrient content, particularly changes in nitrogen. These changes can affect the potential risk to water resources when the products are eventually applied to the land.

3.2.5.1 *Composting*

Solid manure is being composted (the most common treatment for manures) on some Ontario farms.[242] Composting greatly reduces the bulk volume of the material, allowing economic transportation over greater distances than with untreated manure. While the basic requirements for composting are known, many on-farm operations do not achieve complete stabilization. Various recipes exist to mix the various carbon- and nitrogen-contributing materials. Table 3-16 shows the range of nutrient contents in compost.

It is commonly believed that up to 50% of the manure-C may be lost during the composting process. It is not clear what factors are involved in C loss or associated N-losses or the extent of their effects. Applying raw (fresh or non-composted) manure to soil and allowing decomposition to occur in the soil adds more carbon, particularly in compounds that are readily assimilated by microorganisms. This would be expected to stimulate the microbial population, thereby improving soil structural development and stability.

Table 3-16 Typical Nutrient Content of Finished Compost from Manure

Nutrient	Content (% dry weight)
Nitrogen	<1–4.5
Potassium	0.5–1
Phosphorus	0.8–1
Calcium	2–3
Magnesium	2–3

Source: British Columbia, Ministry of Agriculture, Food and Fisheries (BCMAFF), 1993, *Composting Factsheet* (Victoria: Province of British Columbia), Agdex 537/727.

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[242] R.J. Fleming, 1993, *Impacts of Manure Composting*, Water Facts (Toronto: Ontario Ministry of Agriculture and Food, April).

Nitrogen The availability of N in composted cattle manure is much lower than in untreated manure, although release of N appears to continue at a greater rate for several years.[243] N-transformations and ammonia losses occur during the composting process. It is not clear how composting conditions and the composting mixture affect these transformations and hence N-availability to crops. It is believed that significant N-losses may occur if the C:N ratio is too low (e.g., 20–30) but the optimum is not known. During composting, about 50% of the organic matter, 20–30% of the nitrogen, and 40% of the potassium content can be lost if manure is windrowed without covering.[244]

Composting cattle manure in the open resulted in leaching losses of N ranging from 2% to 10% of the NO_3^--N. However, NO_3^--N concentrations generally did not exceed 0.05% of dry matter.[245] Composting is often cited as a way of stabilizing the nitrogen in manure and improving its handling characteristics, but the loss of N in the process has to be considered against these potential benefits.

Phosphorus and other nutrients The availability of phosphorus and other nutrients may also change during composting or other processing. Little information is available to address this issue but the change is probably much less than that for nitrogen.

Bacteria One benefit of properly controlled composting is that harmful bacteria and unwanted weed seeds can be killed (table 3-15). However, it is important to ensure that all the material is subject to temperatures above 55°C, which is difficult in the absence of forced aeration.[246]

Viruses Neither bovine enterovirus nor bovine parvovirus survived aerobic composting for 28 days. Temperature in the pile was maintained at 60°C from day 3.[247]

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243 Paul, 1991.

244 H. Vogtmann and J.M. Besson, 1978, "European composting methods: Treatment and use of farm yard manure and slurry," *Compost Science/Land Utilization*, 19, p. 15; N. Lampkin, 1990, *Organic Farming*, (Ipswich UK: Farming Press Books)

245 Kirchmann, 1985.

246 R. St. Jean, 1997, *On-farm Manure Composting Techniques: Understanding Nitrogen and Carbon Conservation*, Research Report 1.3, COESA Report No. RES/MAN-003/97, Prepared for Agriculture and Agri-Food Canada, London Research Centre, London, Ontario (Prepared by Ecologistics Limited, Waterloo, Ontario. <http://res2.agr.gc.ca/london/env_prog/gp/gpres/report/rep13sum.html>.

247 H.D. Monteith, E.E. Shannon, and J.B. Derbyshire,1986, "The inactivation of bovine enterovirus and a bovine parvovirus in cattle manure by anaerobic digestion, heat treatment, gamma irradiation, ensilage and composting," *Journal of Hygiene*, 97, p. 175.

3.2.5.2 *Other processing treatments*

Other processing treatments commonly address odour formation or gas production, including the volatilization of ammonia.

Mechanical separation of coarse solids from slurry results in a material that can be stacked and composted. The liquid can also be treated more readily because crusts and solid settlement are less of a problem. Such liquids can be aerated in storage to reduce odour release during land application.

Simply separating solids by passing a slurry through a mesh screen can have a significant effect on NH_3 volatilization. However, for cattle slurry, the solids need to be separated using a 0.1 mm mesh to reduce ammonia volatilization by 50%.[248] Acidification of the same slurry to pH 5.5 decreased volatilization by about 85%. Read and Svoboda introduced *Cryptosporidium* oocysts to the liquid remaining after solids were separated from cattle slurry.[249] The material was kept at 15°C with minimal aeration. The dissolved oxygen in the liquid was 0%. The oocysts became non-viable after 4.1 days.

During biogas production (another option for processing manure), much of the manure-N is converted to the ammonium form and is still available in the residues from the process. The anaerobic digesters operate either at ambient temperatures, at which bacteria are not killed, or at elevated temperatures, at which pathogens do not survive if the minimum temperature is at least 55°C. However, the efficiency of digesters can be reduced if the manure contains levels of antibiotics concomitant with therapeutic doses supplied in feed.[250]

Digestion at temperatures below 40°C may not control pathogens, and 10% of *E. coli* and *C. jejuni* may survive for periods in excess of 50 days.[251] However,

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[248] J.P. Frost, R.J. Stevens, and R.J. Laughlin, 1990, "Effect of separation and acidification of cattle slurry on ammonia volatilization and on the efficiency of slurry nitrogen for herbage production," *Journal of Agricultural Science*, 115, p. 49.

[249] I.A. Read and I.F. Svoboda, 1995, "The effect of aerobic treatment on the survivial of *Cryptosporidium parvum* oocysts in cattle slurry," *Protozoan Parasites and Water*, W.B. Betts, D. Casemore, C. Fricker, H. Smith, and J. Watkins (eds.), (Cambridge: Royal Society of Chemistry, UK).

[250] Gamal-El-Din, 1986.

[251] T.E. Kearney, M.J. Larkin, J.P. Frost, and P.N. Levett, 1993, "Survival of pathogenic bacteria during mesophilic digestion of animal waste," *Journal of Applied Bacteriology*, 75, p. 215.

bovine enterovirus and bovine parvovirus survived for only 30 minutes during thermal anaerobic digestion at 55°C, but at 35°C the enterovirus survived for 13 days.[252]

Aerobic treatments to reduce manure odours have been much studied.[253] These treatments are costly, and N-losses are enhanced by ammonia stripping or denitrification of nitrate formed by nitrifiers in liquid manures. This loss of N is agronomically important and represents less sustainable use of resources.

Patent formulas have been promoted as ways to "stabilize" N in manures during storage. No scientific evidence shows that such products are effective to any significant extent for this purpose but there may be some benefits from the reduction of odour.

3.2.5.3 *Summary*

Composting is the most widespread process for manure treatment. Composting stabilizes the remaining nitrogen and improves the manure's handling characteristics, but any loss of N in the process has to be considered against these potential benefits. It is difficult to ensure that all the manure reaches 55°C during the composting process, thereby killing all pathogens.

Other treatments can ensure that manure reaches a sufficiently high temperature to kill pathogens, but in the past these approaches have been too expensive to establish on farms of the size typical in Ontario.

3.2.6 Direct deposition and application of manure to the land

In Ontario, some manure reaches the soil by direct deposition from grazing animals, but the majority is applied as part of the fertilizer requirement for crops. The various stages in manure management to this point determine the concentration and form of nutrients reaching the land, as well as the likelihood that potential microbial contaminants of water will be present.

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[252] Monteith, Shannon, and Derbyshire, 1986.

3.2.6.1 *Direct deposition*

Grazing animals defecate directly onto soil and vegetation. The runoff or leaching of contaminants from grazed fields in Ontario has not been systematically investigated. Runoff water from grazed and ungrazed grass pastures can contain large numbers of bacteria.[254] However, surface runoff does not constitute an important pathway for water or pathogens from pastures to enter streams. Most runoff appears to originate close to the stream bank rather than from the main area of the field.[255] Cattle access to water courses can also contribute to the collapse of banks and entry of soil, nutrients, and pathogens into the water.[256] Once in surface water, the survival of *E. coli* (ETEC), *Campylobacter jejuni* and *Yersinia enterocolitica* is such that this could be a persistent site of transmission between animals and humans.[257]

If drinking water wells in shallow aquifers are poorly maintained or badly located, they can be impacted by surface runoff. There is evidence of a child being infected with *E. coli* O157:H7 from dairy cattle through drinking water from such a well.[258]

Ammonia volatilization and N-leaching was greater from grassland grazed by cattle than by sheep.[259] Some NH_3 volatilized from urine patches is intercepted by vegetation downwind. This reduces the total gaseous loss of N.

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[253] E.g., J. Pos, R.G. Bell, and J.B. Robinson, 1971, "Aerobic treatment of liquid and solid poultry manure," *Livestock Waste Management and Pollution Abatement*, Proceedings of the International Symposium on Livestock Wastes, Columbus, Ohio (St Joseph, MI: American Society of Agricultural Engineers); T. Al-Kanani, E. Akochi, A.F. Mackenzie, I.A. Ali and S.F. Barrington, 1992a, "Odour control in liquid hog manure by added amendments and aeration," *Journal of Environmental Quality*, 21, p. 704.
[254] H. Kirchmann, 1994, "Animal and municipal organic wastes and water quality," *Advances in Soil Science: Soil Processes and Water Quality*, R. Lal and B.A. Stewart (eds.), (Boca Raton, FL: CRC Press), p. 163.
[255] J.C. Buckhouse and C.C. Bohn, 1983, "Response of coliform bacteria concentration to grazing management: Livestock grazing systems in relation to fecal contamination of rangelands, watersheds, runoff, non-point source pollution, stream monitoring," *Research in Rangeland Management*, Special Report 682, Agricultural Experiment Station, Oregon State University, p. 1.
[256] E.A. Clark, 1998, "Landscape variables affecting livestock impacts on water quality in the humid temperate zone," *Canadian Journal of Plant Science*, 78, p. 181.
[257] S.I. Terzieva and G.A. McFeters, 1991, "Survival and injury of *Escherichia coli*, *Campylobacter jejuni* and *Yersinia enterocolitica* in stream water," *Canadian Journal of Microbiology*, 37, p. 785.
[258] S.G. Jackson, R.B. Goodbrand, R.P. Johnson, V.G. Odorico, D. Alves, K. Rahn, J.B. Wilson, M.K. Welch, and R. Khakhria, 1998, "*Escherichia coli* O157:H7 diarrhoea associated with well water and infected cattle on an Ontario farm," *Epidemiology and Infection*, 120, p. 17.
[259] S.C. Jarvis, D.J. Hatch, and D. H. Roberts, 1989a, "The effects of grassland management on nitrogen losses from grazed swards through ammonia volatilization; the relationship to excretal N

Evidence from the UK suggests that leaching of NO_3^- from grazed pastures is greater than for cut forage because the urine is excreted in patches. Soil under these patches can contain large amounts of N that cannot be adsorbed by the vegetation at a rate sufficient to prevent leaching.[260] In this respect, fertilized pastures do not appear to differ much from pastures comprised of a mixture of grass and legumes.[261] Groundwater loadings of N by leaching from these pastures are comparable with or even exceed those from arable land.[262] However, grazed land in Ontario is likely used by fewer animals and for a shorter period each year than that in the UK, so the leaching loss of N is likely to be significantly less.

3.2.6.2 *Application to land*

On most livestock farms the manure is applied to land, particularly cropped land.[263] Solid manure lends itself only to surface spreading which then requires a second tillage operation for incorporation. Liquid manure can be spread from a tanker, applied by irrigation, or injected using hollow tines. After spreading, liquid manure may also be incorporated by tillage. Application of liquid manure adds solids plus water, thereby increasing soil water content. This effect may be sufficient to result in flow through tile drains. Applying solid manure causes little change in soil water content.

Almost all of the incidents of water course contamination in the Southwestern Region of Ontario were related to land application of manure. Results from the *Ontario Farm Groundwater Quality Survey* indicated that farmstead drinking-water wells were more likely to be contaminated where manure was spread.[264]

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returns from cattle," *Journal of Agricultural Science* (Cambridge), 112, p. 205; S.C. Jarvis, J.H. Macduff, J.R. Williams, and D.J. Hatch, 1989b, "Balances of forms of mineral N in grazed grassland soils: Impact on N losses," *Proceedings of the XVI International Grassland Congress*, Nice, p. 151.

[260] S.P. Cuttle and D. Scholefield, 1995, "Management options to limit nitrate leaching from grassland," *Journal of Contaminant Hydrology*, 20, p. 299.

[261] N.J. Hutchings and I.S. Kristensen, 1995, "Modelling mineral nitrogen accumulation in grazed pasture: Will more nitrogen leach from fertilized grass than unfertilized grass/clover?" *Grass and Forage Science*, 50, p. 300.

[262] J.C. Ryden, P.R. Ball, and E.A. Garwood, 1984, "Nitrate leaching from grassland," *Nature* (London), 311, p. 50.

[263] Baldwin, 1981.

[264] Goss, Barry, and Rudolph, 1998a, D.L. Rudolph, D.A.J. Barry, and M.J. Goss, 1998b, "Contamination in Ontario farmstead domestic wells and its association with agriculture: 2. Results from multilevel monitoring well installations," *Journal of Contaminant Hydrology*, 32, p. 295.

Volatilization of ammonia represents the largest loss of N from manure. Beauchamp et al. and Paul et al. found that the three most important variables that influence NH_3 volatilization appear to be temperature, soil pH, and soil texture.[265] Other gaseous losses primarily influence the amount of NO_3^--N that remains in the soil, available to plants or for leaching to groundwater. The gaseous loss, together with the rate at which organic nitrogen is mineralized, result in considerable uncertainty about the availability of manure-N once it is incorporated in the soil. For example, Pratt et al. observed that a greater proportion of N could not be accounted for at an application of 1750 kg/ha N than at 500 kg/ha N.[266] Beauchamp found that only about three-quarters of the ammonium-N fraction was as available as an equivalent mass of fertilizer-N.[267]

Transportation of manure to sites of application Liquid manure is transported via pipelines, tanker-trailers, or custom truck-spreaders. Equipment manufacturers have increased tanker size to meet market demands. The mass of tanker and contents often exceeds the capacity of the tractor brakes to stop a fully loaded unit, which could lead to a spill.

Semi-solid manure is not easily transported and can result in spillage in transit. Solid manure is somewhat easier to transport. The cost of transportation is high because of the large volume-to-weight ratio and the relatively small concentration of nutrients. Poultry manure tends to be the exception, and poultry producers have greater opportunities to have the manure taken by other farmers.

The cost of transportation has also resulted in manure being spread more regularly on fields close to the barn or storage than on more distant fields. The nutrient levels, particularly of nutrients such as phosphorus that are less mobile in the soil, can become excessive if such practices have continued over many years. Nutrient management strategies are designed to ensure that excess nutrients are not applied to the land, thereby reducing the risk to water resources. However, implementing such strategies also means that manure needs to be transported

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[265] E.G. Beauchamp, G.E. Kidd, and G. Thurtell, 1982, "Ammonia volatilization from liquid dairy cattle manure in the field," *Canadian Journal of Soil Science*, 62, p. 11; J.W. Paul, E.G. Beauchamp, H.R. Whiteley, and J.K. Sakupwanya, 1990, *Fate of Manure Nitrogen at the Arkell and Elora Research Stations 1988–1990*, Report on Special Research Contract No. SR8710-SW001, Ontario Ministry of Agriculture and Food.

[266] P.F. Pratt, A.E.M. Chirnside, and R.G. Scarborough, 1976, "A four-year field trial with animal manures," *Hilgardia*, 44, p. 99.

[267] E.G. Beauchamp, 1986, "Availability of nitrogen from three manures to corn in the field," *Canadian Journal of Soil Science*, 66, p. 713.

farther from the storage sites, which may mean increased transportation from one farm to another.

Transportation of manure to the field has been a factor in some manure spills, but it is the application, mainly of liquid manure, that is the most frequently reported cause of manure entering surface water bodies.

Impacts of application techniques There are three main methods of application: broadcasting (solid, semi-solid, and liquid manure), irrigation, and injection (liquid manure). The mode of application has the greatest effect on the amount of volatilization of ammonia. Importantly, the more nitrogen lost through this route, the less that is potentially available to be lost to water resources, but the impacts on the environment are more extensive and associated odour issues greater.

Liquid manure is applied to the soil surface of arable land either from a tanker (broadcasting) or by using a sprayer linked to pipes that are connected to the storage system (irrigation). Broadcasting has traditionally used a splash-plate to distribute the manure, but low-level or low-pressure nozzles on booms are increasingly used. These give a more even distribution or can be used to apply the manure in bands between rows, thereby reducing odour release. Liquid manure can also be directly injected below the soil surface (injection), using hollow tines preceded by coulters to cut through crop residues. The injector system can be mounted directly behind a tanker or set on a tool bar connected to the three-point hitch of a tractor and linked to a stationary tanker via a flexible hose.

Broadcast application of liquid manure from a tanker has resulted in fewer than a third of the problems encountered when using spray irrigation, a practice that is declining in popularity. Equipment failure has been the cause of 27% of spills associated with the land application of manure.

The techniques for both irrigation and injection are well developed, and manufacturers continue to improve the equipment for surface-spreading liquid manure from tankers. They are improving the uniformity of application, which also helps to reduce odour. Flow meters enable operators to apply liquid manure more judiciously.

The availability of nutrients, particularly nitrogen, to a subsequent crop differs between these two systems for manure application, mainly because of differences in the potential for gaseous losses (table 3-17).[268] Ammonia loss during sprinkler irrigation of pig manure ranged from 14–37% of total Kjeldahl nitrogen present in the slurry.[269] The pH of the slurry also increased, which would promote greater volatilization once the manure reached the soil. Band-spreading reduces NH_3 volatilization compared with splash plates.

Up to 100% of the ammonia present in applied manures may be lost within a few days to a few weeks if left on the soil surface.[270] When liquid cattle manure was injected as a side-dressing for corn, the N was 60% as available fertilizer-N. When the manure was surface-applied as a side dressing, its N was only 33% as available fertilizer-N. The reduced availability was attributed to ammonia volatilization.[271]

The total nitrogen available to crops is generally greater after injection than after surface spreading, with injection reducing ammonia volatilization by 85–95% compared with surface spreading.[272] Furthermore, the possibility of surface runoff immediately after application is greater with surface spreading than injection.

Table 3-17 Comparison of Different Methods of Manure Application on the Losses of Ammonia by Volatilization

Method of Application	Type of Waste	% Nitrogen lost
		0–7 days
Broadcast	Solid Liquid	15–30 10–27
Broadcast with immediate cultivation	Solid Liquid	1–5 1–8
Injection	Liquid	1–5
Sprinkler irrigation	Liquid	14–37

Sources: R.J. Fleming, 1988, *An Expert System for the Selection/Design of Swine Manure Handling Methods*, M.Sc. Thesis, Univ. of Guelph; J.J. Meisinger and G.W. Randall, 1991, "Estimating nitrogen budgets for soil-crop system," *Managing Nitrogen for Groundwater Quality and Farm Profitability,* R.F. Follet, D.R. Keeney, and R.M. Cruse (eds.) (Madison, WI: SSSA), p. 85; J. Van der Molen, H.E. Van Faasen, M.Y. Leclerc, R. Vriesma, and W.J. Chardon, 1990a, "Ammonia volatilisation from arable land after application of cattle slurry: 1. Field estimates." *Netherlands Journal of Agricultural Science*, 38, p. 145.

[268] Ibid.
[269] L.M. Safley Jr., J.C. Baker, and P.W. Westerman, 1992, "Loss of nitrogen during sprinkler irrigation of swine lagoon liquid," *Bioresource Technology*, 40, p. 7.
[270] Beauchamp, Kidd, and Thurtell, 1982; Paul et al., 1990.
[271] Beauchamp, 1983.
[272] Paul, 1991.

Incorporating manure by tillage immediately after application dramatically reduces runoff losses. In trials using simulated rainfall, King et al. found that more NH_4^+ and phosphorus were lost in surface runoff immediately following surface spreading than after incorporation or injection of manure.[273] Generally, runoff-N losses are small, 3 kg/ha N annually or less.[274] However, a considerable amount of runoff may occur in the presence of a shallow hardpan.[275] Large losses of N can occur by subsurface flow through tile drains.[276] On arable land in the Netherlands, losses of N through tile drains averaged as much as 22 kg N/ha/y during a 10-year period.[277]

Although injection has been recommended to reduce the losses from volatilization, gaseous loss associated with this technique mainly results from denitrification rather than NH_3 volatilization.[278] The denitrification occurred mainly in the region immediately around the slit.[279] Compared with broadcasting, injection requires greater tractor power and less manure can be applied per hour. Therefore, cost and the small window of time available to most farmers in the spring often limit the potential use of injection.

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[273] D.J. King, G.C. Watson, G.J. Wall, and B.A. Grant, 1994, *The Effects of Livestock Manure Application and Management on Surface Water Quality, Summary Technical Report* (London, ON: GLWQP-AAFC Pest Management Research Centre, Agriculture and Agri-Food Canada).

[274] D.J. Nichols, T.C. Daniel, and D.R. Edwards, 1994, "Nutrient runoff from pasture after incorporation of poultry litter of inorganic fertilizer," *Soil Science Society of America Journal*, 58, p. 1224; Meisinger and Randall, 1991; D.W. Blevins, D.H. Wilkison, B.P. Kelly, and S.R. Silva, 1996, "Movement of nitrate fertilizer to glacial till and runoff from a claypan soil," *Journal of Environmental Quality*, 25, p. 584; G.J. Gascho, R.D. Wauchope, and J.G. Davis, 1998, "Nitrate-nitrogen, soluble, and bioavailable phosphorus runoff from simulated rainfall after fertilizer application," *Soil Science Society of America Journal*, 62, p. 1711.

[275] M.J. Goss, K.R. Howse, P.W. Lane, D.G. Christian, and G.L. Harris, 1993, "Losses of nitrate-nitrogen in water draining from under autumn crops established by direct drilling or mouldboard ploughing," *Journal of Soil Science*, 44, p. 35; R.K. Hubbard, R.A. Leonard, and A.W. Johnson, 1991, "Nitrate transport on a sandy coastal plain soil underlain by plinthite," *Transactions of the American Society of Agricultural Engineers*, 34, p. 802; R. Lowrance, 1992, "Nitrogen outputs from a field-size agricultural watershed," *Journal of Environmental Quality*, 21, p. 602.

[276] A.J.A. Vinten, 1999, "Predicting nitrate leaching from drained arable soils derived from glacial till," *Journal of Environmental Quality*, 28, p. 988.

[277] G.J. Kolenbrander, 1969, "Nitrate content and nitrogen loss in drainwater," *Netherlands Journal of Agricultural Science*, 17, p. 246.

[278] R.B. Thompson, J.C. Ryden, and D.R. Lockyer, 1987, "Fate of nitrogen in cattle slurry following surface application or injection to grassland," *Journal of Soil Science*, 38, p. 689; S.D. Comfort, K.A. Kelling, D.R. Keeney, and J.C. Converse, 1990, "Nitrous oxide production from injected liquid dairy manure.," *Soil Science Society of America Journal*, 54, p. 421.

[279] S.O. Petersen, 1992, "Nitrification and denitrification after direct injection of liquid cattle manure," *Acta Agriculturae Scandinavica. Section B, Soil and Plant Science*, 42, p. 94.

Poor distribution patterns result from all types of manure spreaders due largely to the nature of the material. Using injection on rolling topography has also resulted in problems.

The most frequently reported route by which liquid manure can contaminate surface water courses is in outflow from tile-drain systems. Fleming and Bradshaw identified macropore flow of manure liquids into subsurface drains after spreading.[280] Pre-tillage tines have been incorporated into injection machinery to limit macropore flow (J. Houle & Fils Inc., Drummondville, Quebec; Husky Farm Equipment Ltd., Alma, Ontario).

Large tankers can cause problems with soil compaction in the field. Compaction is a significant concern because it can increase surface runoff as well as decrease crop yield. This problem is also being reduced by new machine design (e.g., tankers with tracks now made by Husky Mfg.).

Solid manure is applied by spreader machines that propel the manure to the rear or to the side. Although new machines operate effectively, the spread tends to become less uniform with use. The more variable nature of solid manure also tends to reduce the uniformity of nutrient application.

Bacteria Evidence from the Ausable-Bayfield Conservation Authority indicates that bacteriological contamination from tile drains can be greater after injection than after surface spreading.[281] Transport of bacteria in surface runoff was similar for surface spreading, incorporation, or injection of manure.[282] When the system was modified by placing a cultivating tine ahead of the injector tine, there was a significant reduction in bacterial transport through runoff. Pre-tillage of soil before spreading liquid manure minimized the direct impact of manure on the quality of tile-drain effluent.[283]

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[280] R.J. Fleming and S.H. Bradshaw, 1991, *Macropore Flow of Liquid Manure* (Saskatoon, SK: Canadian Society Agric. Eng.), Paper No. 91-241; R.J. Fleming and S.H. Bradshaw, 1992a, *Detection of Soil Macropores Using Smoke* (Saskatoon, SK: Can. Soc. Agric. Eng.), Paper No. 92-103; R.J. Fleming and S.H. Bradshaw, 1992b, *Contamination of Subsurface Drainage Systems during Manure Spreading* (St. Joseph, MI: Am. Soc. Agric. Eng.), Paper No. 92-2618.
[281] M.E. Foran, D.M. Dean, and H.E. Taylor, 1993, "The land application of liquid manure and its effect on tile drain water and groundwater quality," *Agricultural Research to Protect Water Quality: Proceedings of the Conference.* February 21–24, Minneapolis, MN (Ankeny, IA: Soil and Water Conservation Society), p. 279.
[282] King et al., 1994.
[283] Fleming and Bradshaw, 1992b.

Bacteria from poultry manure were not detected in runoff when the manure was applied to bare soil, but was present when the manure was applied to grassland.[284] 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.[285]

Timing of manure applications When determining when to apply manure, producers have to consider several factors including the risk of soil compaction, likelihood of runoff, and nutrient loss through NH_3 volatilization. The timing of manure applications is critical both for the availability of nitrogen to crops and for potential impacts on the environment. As manure storage on many farms is limited, the common periods for application are the fall, winter, and spring. In spring, applications may be as a pre-plant fertilization or as a side- or top-dressing. The experimental evidence shows that compared with spring applications, manuring land in fall or winter results in lower recovery of applied nitrogen by the crops and greater risk of leaching or surface runoff and denitrification (table 3-18).[286]

Current guidelines in Ontario state that manure should "not be spread on frozen or ice-covered soil." If the soil is unfrozen, then winter spreading should not occur on land with more than a slope of 3%. In an emergency, winter spreading is permitted, but only on land with residues or vegetation and only where there is no danger of runoff or flooding.

Fleming and Fraser have reviewed the literature on winter spreading of manure in Ontario.[287] In general, winter spreading of manure results in greater nutrient losses than at other times. As many soils are impervious when frozen, manure spread on the surface is likely to be carried off in runoff from snow-melt or rain. The likelihood of surface runoff does not appear to differ whether the manure is spread on frozen soil or snow or onto a cover crop.

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[284] J. Giddens and A.P. Barnett, 1980, "Soil loss and microbiological quality of runoff from land treated with poultry litter," *Journal of Environmental Quality*, 9, p. 518.
[285] King et al., 1994
[286] Thompson, Ryden, and Lockyer, 1987; M.J. Goss, W.E. Curnoe, E.G. Beauchamp, P.S. Smith, B.D.C. Nunn, and D.A.J. Barry, 1995a, *An Investigation into the Management of Manure Nitrogen to Safeguard the Quality of Groundwater*, COESA Report No. LMAP- 013/95 prepared for Research Branch. Agriculture and Agri-Food Canada.
[287] R. Fleming and H. Fraser, 2000, *Impacts of Winter Spreading of Manure on Water Quality: Literature Review* (Ridgetown, ON: Ridgetown College, University of Guelph).

The effect of slope has received little critical attention. Losses to the environment depend on whether the first snow-melt or rainfall event results in runoff or infiltration, which is greatly influenced by weather factors. However, solid manure may reduce the amount of runoff. Loss of NH_3 by volatilization may be reduced if the manure is covered by snow after application. Clearly, as current weather patterns are critical, it is difficult to predict whether there will be significant environmental contamination in any one winter. Local weather records might be used to identify locations where the risks are greatest, but Fleming and Fraser concluded that the evidence supports the adherence to the current guidelines for spreading.[288]

Table 3-18 Sinks for N Following Application of Slurry

	Nitrogen Sinks†			
Application	**Apparent Recovery in Herbage**	**NH_3 Volatilization Loss**	**Denitrification Loss**	**Total Sinks**
Winter Experiment	kg N/ha (%)			
Surface spread slurry	49.0 (19.8)	77.1 (30.8)	29.9 (12.1)	156.1 (62.9)
Injected slurry	82.7 (33.4)	2.1 (0.9)	52.7 (21.3)	137.5 (55.4)
Injected slurry † plus nitrapyrin (nitrification inhibitor)	90.1 (36.3)	2.1 (0.9)	22.7 (9.2)	114.9 (46.3)
CV‡	17.0%	25.3%	98.2% (42.6%)	–
Spring Experiment				
Surface spread slurry	66.9 (25.5)	53.0 (20.2)	4.5 (1.7)	124.4 (47.5)
Injected slurry	93.9 (35.5)	2.4 (0.9)	17.7 (6.8)	114.0 (43.5)
Injected slurry † with nitrapyrin	109.9 (42.0)	2.4 (0.9)	14.0 (5.3)	126.3 (48.2)
CV‡	13.8%	21.1%	182% (74.8%)	–

† In both experiments leaching losses from all treatments were negligible
‡ Coefficients of variation determined as follows:
Apparent recovery: from the total apparent recoveries for each of the four plots for the three treatments in each experiment.
NH_3 volatilization: from the total NH_3 loss determined for each of the three tunnels used for the surface application treatment.
Denitrification: the average coefficient of variation for all denitrification measurements in each experiment. In parentheses, the average for values greater than 0.10 kg N/ha/d.
Source: Thompson et al., 1987.

[288] Ibid.

Effect of manure treatment and soil conditions on NH_3 volatilization As indicated above, much research has been devoted to examining the loss of ammonia to the atmosphere due to volatilization after surface applications of manure. Loss from bare soil is less than losses from grassland,[289] arable land with surface residues, or growing crops.[290]

Key factors that influence the volatilization from surface-applied slurries are wind speed, temperature, the pH at the surface of the slurry, and its dry matter content.[291] After adjusting for pH and temperature, Sommer and Olesen found a sigmoid relationship between the cumulative loss of ammonia and the dry matter content, such that the loss was greatest for a dry matter content between 4% and 12%.[292]

A transfer model related the rate of ammonia volatilization to the concentration of the gas at the surface of a layer of slurry and the background concentration in the atmosphere.[293] The model takes into account the depth of soil in which the slurry is distributed, evaporation of soil water, and infiltration of rain. Before it can be used by farmers, the model needs to be extended to predict pH at the volatilizing surface since this also affects the rate of loss.

The effect of mechanically removing particulate organic matter from slurry applied to grassland has been examined. Thompson et al. found that in the initial 5 h, the rate of NH_3 volatilization was slower from cattle slurry that had passed through a 3 mm mesh than from unseparated slurry.[294] Later the relative rates were reversed, so that the losses from the two treatments over 6 days were

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[289] R.B. Thompson, J.C. Ryden, and D.R. Lockyer, 1990, “Ammonia volatilization from cattle slurry following surface application to grassland,” *Plant and Soil*, 125, p. 109.
[290] H.-G. Bless, R. Beinhauer, and B. Sattelmacher, 1991, “Ammonia emissions from slurry applied to wheat stubble and rape in North Germany,” *Journal of Agricultural Science*, 117, p. 225.
[291] R. Van den Abbeel, D. Paulus, C. De Ruysscher, and K. Vlassak, 1990, “Gaseous N losses after the application of slurry: Important or not?” *Fertilization and the Environment*, R. Merckx, H. Vereecken, and K. Vlassak (eds.), (Leuven, Belgium: Leuven University Press), p. 241; S.G. Sommer, J.E. Olesen, and B.T. Christensen, 1991, “Effects of temperature, wind speed and air humidity on ammonia volatilization from surface-applied cattle slurry,” *Journal of Agricultural Science* (Cambridge), 117, p. 91.
[292] S.G. Sommer and J.E. Olesen, 1991, “Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry,” *Journal of Environmental Quality*, 20, p. 679.
[293] J. Van der Molen, A.C.M. Beljaars, W.J. Chardon, W.A. Jury, and H.G. Van Faasen, 1990b, “Ammonia volatilisation from arable land after application of cattle slurry: 2. Derivation of a transfer model,” *Netherlands Journal of Agricultural Science*, 38, p. 239.
[294] Thompson, Ryden, and Lockyer, 1990.

35% and 38% respectively. Stevens et al. investigated particle separation, dilution, and a washing treatment for cattle slurry applied to grassland.[295] A 50% reduction in NH_3 volatilization, compared with untreated slurry, could be obtained by removing solids using a 0.4 mm mesh, or using a 10 mm mesh and diluting the strained material with 86% by volume of water, or by using a 2 mm mesh and washing with a 53% volume of water after manure application.

Acidification of manure is potentially one way of reducing volatilization of ammonia and hence nitrogen loss. Stevens et al. observed a 90% decrease in volatilization by acidifying cattle slurry to pH 6.[296] Acidifying cattle slurry to pH 5.5 reduced volatilization by 14 to 57%.[297] Acidifying pig slurry and adding sphagnum peat moss also decreased ammonia volatilization by at least 74.6%.[298] Elemental sulphur and calcium carbonate increased the volatilization. While acidification alone did not reduce the effectiveness of the slurry nitrogen for wheat growth, the combination of 1% sphagnum moss and calcium carbonate impaired plant growth. Adding 1.4% by volume of 10 molar nitric acid to slurry reduced volatilization by 75% compared with unamended slurry, and increased the nitrogen content of the slurry by 2 g N/L. The acidified slurry had a superior balance of mineral N, P, and K for fertilizing grass. However, in practice, acidification of manure has not been found to be cost-effective.[299]

A combination of acidification and solids separation can produce benefits. Stevens et al. obtained the same 90% decrease in volatilization by acidification to pH 6.5 together with dilution with a 50% volume of water, and by acidification to 6.5 following removal of solids using a 0.4 mm mesh.[300] For acidified whole slurry, the efficiency of nitrogen use was only 54% of that for mineral fertilizer.[301] However, after removal of solids using a 1.1 mm mesh and acidification, the efficiency of

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[295] R.J. Stevens, R.J. Laughlin, and J.P. Frost, 1992a, "Effects of separation, dilution, washing and acidification on ammonium volatilization from surface applied cattle slurry," *Journal of Agricultural Science* (Cambridge), 119, p. 383.
[296] Ibid.
[297] B.F. Pain, R.B. Thompson, Y.J. Rees, and J.H. Skinner, 1990, "Reducing gaseous losses of nitrogen from cattle slurry applied to grassland by the use of additives," *Journal of the Science of Food and Agriculture*, 50, p. 141.
[298] T. Al-Kanani, E. Akochi, A.F. Mackenzie, I.A. Ali, and S.F. Barrington, 1992b, "Organic and inorganic amendments to reduce ammonia losses from liquid hog manure," *Journal of Environmental Quality*, 21, p. 709.
[299] R.J. Stevens, 1997, [personal communication].
[300] Stevens, Laughlin, and Frost, 1992a.
[301] R.J. Stevens, R.J. Laughlin, J.P. Frost, and R. Anderson, 1992b, "Evaluation of separation plus acidification with nitric acid and separation plus dilution to make cattle slurry a balanced, efficient fertilizer for grass and silage," *Journal of Agricultural Science* (Cambridge), 119, p. 391.

nitrogen use from the slurry was 88%. The lower efficiency of the whole slurry was attributed to enhanced denitrification and contamination of plant leaves.

Some other manure treatments appear to have little effect on the conservation of ammonia after land application. Volatilization of ammonia from grassland was the same for unamended pig slurry and pig slurry treated by anaerobic digestion.[302]

3.2.6.3 *Summary*

There has been no systematic investigation of the runoff or leaching of contaminants from grazed fields in Ontario. It is considered that surface runoff is not an important pathway for water or pathogens from pastures to enter streams. Most runoff originates close to the stream bank rather than from the main area of the field. Cattle accessing watercourses also contribute to soil, nutrients, and pathogens entering the water. Because grazing animals excrete urine and feces in patches, nitrate leaching from grazed pastures is greater than from cut forage. Groundwater loading of N by leaching from grazed land can compare with or even exceed that from arable land, but current stocking rates in Ontario make this loading unlikely to be a significant source of groundwater contamination.

Most manure is applied to cropped land. Solid manure is surface spread. Transporting manure to the field has been a factor in some manure spills, but the application of (mainly liquid) manure has been the most frequently reported cause of manure entering surface water bodies. Liquid manure may be surface spread from a tanker, applied by irrigation, or injected using hollow tines. The mode of application greatly affects the volatilization of ammonia. Sprinkler irrigation tends to result in the greatest gaseous loss on application, but failure to incorporate liquid manure after application can also result in large losses.

The type of application can influence the loss of potential contaminants to surface and groundwater. Potential for NO_3^- leaching after application can be influenced by the volatilization of NH_3 at application. Incorporating the manure after application helps conserve nitrogen, but manure treatment has little effect on gaseous loss. Application to no-till land provides greater opportunity for gaseous loss, but leaving manure on the surface of bare soil can also encourage runoff. Bacterial movement into tile lines can be greater after injection than after surface application.

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[302] Pain et al., 1990.

The timing of application also affects the risk of water contamination, with fall, winter, and early spring applications likely to have the most negative impacts.

3.2.7 Fate of manure components applied to the soil

The producer applies manure to meet the nutrient demands of the crop. However, because the ratio of N, P, and K in manure is not identical to crop requirements, additional mineral fertilizer may be required if excess application of P or K is to be avoided. After field application, manure forms a diffuse source. The nutrients in the manure may be taken up by the crops or become available for transport. Nitrogen can be lost in gaseous form as ammonia or nitrified to nitrate which is then subject to leaching or denitrification.

3.2.7.1 *Nitrogen*

The proportion of the total-N present in the ammoniacal (NH_3 and NH_4^+) form is a key manure characteristic for two reasons: it can be lost as gaseous ammonia and it is generally thought of as being as available as the N in granular fertilizer.[303] However, when mixed in soil, ammoniacal-N is not quite as available as fertilizer-N. It may be immobilized by being taken up by soil microbes or adsorbed onto clays.[304] To preserve nutrients following surface spreading, the material needs to be tilled into the soil as soon as possible after application, particularly to minimize the loss of ammonia by volatilization. Incorporating manure reduced the ammonia volatilization from 32% of total ammoniacal nitrogen to about 16%.[305] Nevertheless, incorporation is not always possible. Overall, our ability to predict losses following application is far from complete.

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[303] E.G. Beauchamp and J.W. Paul, 1989, "A simple model to predict manure nitrogen availability to crops," *Nitrogen in Organic Wastes Applied to Soils,* J.A. Hansen and and K. Henrikson (eds.), (London: Academic Press), p. 140; Beauchamp, 1983.

[304] T.H. Flowers and P.W. Arnold, 1983, "Immobilization and mineralization of nitrogen in soils incubated with pig slurry or ammonium sulphate," *Soil Biology & Biochemistry*, 15, p. 329; T.Z. Castellanos and P.F. Pratt, 1981, "Mineralization of manure nitrogen: Correlation with laboratory indexes," *Soil Science Society of America Journal*, 45, p. 354; Beauchamp, 1986; J.W. Paul and E.G. Beauchamp, 1994, "Short-term nitrogen dynamics in soil amended with fresh and composted cattle manures," *Canadian Journal of Soil Science*, 74, p. 147.

[305] Van der Molen et al., 1990a.

Within the soil, the ammonium ions in the manure are added to those resulting from mineralization of organic nitrogen in soil organic matter and from organic forms in the manure.

The NH_4^+ ions undergo oxidative reactions first to form nitrite (NO_2^-) and then nitrate (NO_3^-), but some convert into dissolved ammonia and are subject to volatilization.[306] Very little NO_2^- is present in most soils in Ontario because it is rapidly converted to NO_3^-. Both NO_3^- and NH_4^+ can be taken up by plants, but are also subject to further transformations. NO_3^- can be converted to gaseous nitrous oxide and nitrogen gas under anaerobic conditions. This denitrification process occurs more readily with organic nitrogen sources such as livestock manure. The amount of subsurface denitrification is a function of manure type, soil type, time of application, and depth to groundwater.[307] In contrast, the remaining organic-N fraction of manure may be only marginally available in the year of application.[308] The degradability of the organic fraction of manure is not well understood in terms of the N-release dynamics in the field.

Few researchers have reported losses of nitrous oxide from cropped land fertilized with manure, but losses under corn were comparable with losses from grassland given much greater nitrogen applications.[309]

The organic matter in cattle manure provides additional carbon substrate for denitrifying bacteria in the soil. This can stimulate denitrification for long periods after slurry applications. The emission of gases such as N_2O, NO, and NO_2 due to denitrification from manured soils is likely to be greater than that from soils receiving mineral nitrogen fertilizers.[310] Effect of the application of

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306 Beauchamp, 1983; Thompson, Ryden, and Lockyer, 1987.

307 Just as ammonia volatilization can reduce the amount of N available for leaching, denitrification below the root zone, or in riparian zones and wetlands, can reduce the amount of NO_3^- available to move to a water resource. However, the proportion of NO_3^- that is reduced to nitrogen gas (N_2) (rather than to N_2O, a greenhouse gas) is uncertain and not easily controlled. Consequently, it is still better to minimize leaching of NO_3^- rather than encouraging denitrification to protect water resources; D.L. Burton, E.G. Beauchamp, R.G. Kachanoski, and R.W. Gillham, 1991, "Impact of livestock manure and fertilizer application on nitrate contamination of groundwater," *Proceedings – Environmental Research: 1991 Technology Transfer Conference, Volume I.* Toronto, ON, November 1991, Research and Technology Branch, Environment ON, p. 180.

308 Beauchamp, 1986; Paul, 1991.

309 M.J. Eichner, 1990, "Nitrous oxide emissions from fertilized soils: Summary of available data," *Journal of Environmental Quality*, 19, p. 272.

310 R.B. Thompson and B.F. Pain, 1990, "The significance of gaseous losses of nitrogen from livestock slurries applied to agricultural land," *Fertilization and the Environment*, R. Merckx, H. Vereecken, and K. Vlassak (eds.), (Leuven, Belgium: Leuven University Press), p. 290.

unamended cattle slurry to grassland was tested by Burford et al.[311] The air in the soil under a layer containing slurry was found to contain up to 680 ppm of N_2O. The actual gaseous loss of nitrogen was not determined, but was deemed significant. It was suggested that further work be carried out investigating gaseous transfer. Paul et al. showed that manured soil produced N_2O and NO due to nitrification and denitrification processes.[312] Production of the gases was greater when the manure was applied as slurry than as compost. As a minimum water content of the soil was important for denitrification losses from manure,[313] the additional water applied could have been an important factor in generating losses from the slurry.

Pain et al. observed a rate of 0.91 kg N/ha/day for denitrification a few weeks after slurry application to a freely drained loam soil in the fall.[314] The total losses were about 29% of the ammoniacal-N applied. Acidification of the manure increased the loss to 41% of the applied ammonium-N. The nitrification inhibitor, dicyandiamide, reduced denitrification to an extent depending on the concentration applied in the slurry. Another nitrification inhibitor, nitrapyrin, had little effect on the rate of denitrification (table 3-18). Denitrification after a spring application was much less than that after a fall application on this soil, and little took place from a poorly drained loam after applying manure at either time. Surface application of manure in summer was associated with smaller losses of nitrogen by denitrification.[315]

Clearly, the information already presented establishes that volatilization of NH_3 is a major route for N-loss during and immediately after manure application. The magnitude of all the gaseous losses of N is difficult to estimate. Consequently, reports suggest (see section 3.2.8) that ground-water contamination with NO_3^- is

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[311] J.R. Burford, D.J. Greenland, and B.F. Pain, 1976, "Effects of heavy dressings of slurry and inorganic fertilizers applied to grassland on the composition of drainage waters and the soil atmosphere," *Agriculture and Water Quality. Technical Bulletin. No. 32* (London: Ministry of Agriculture, Fisheries and Food), p. 432.

[312] J.W. Paul, E.G. Beauchamp, and X. Zhang, 1993, "Nitrous and nitric oxide emissions during nitrification and denitrification from manure-amended soil in the laboratory," *Canadian Journal of Soil Science*, 73, p. 539.

[313] S.G. Nugroho and S. Kuwatsuka, 1990, "Concurrent observation of several processes of nitrogen metabolism in soil amended with organic materials. I. Effect of different organic materials on ammonification, nitrification, denitrification, and N_2 fixation under aerobic and anaerobic conditions," *Soil Science and Plant Nutrition*, 36, p. 215.

[314] Pain et al., 1990.

[315] Van den Abbeel et al., 1990.

greater in areas where animal manure is applied regularly compared with areas receiving predominantly mineral-N fertilizer.[316]

3.2.7.2 *Phosphorus and other nutrients*

Many fields in Ontario that have received regular applications of manure contain large amounts of phosphorus. Applying increasing amounts of cattle manure to soils in Alberta over 11 years enhanced the total phosphorus content of the soil and the available phosphorus.[317] From agronomic considerations, one would want to apply only as much phosphorus, either as manure or fertilizer, as is required for most economic crop production. Current recommendations assume that 40% of the phosphorus in manure is as available in the year of application as from commercial fertilizer.[318] However, this assumption has not been tested thoroughly and probably underestimates the actual value. A 50–60% availability of manure-P is usually assumed in the UK.[319] While 29–39% of P in liquid manure from cattle, poultry, and swine was apparently recovered in plants under greenhouse conditions, 42% of fertilizer-P was recovered.[320] This means that manure-P would be up to 93% as available as from commercial fertilizer.

The phosphorus applied may be combined in inorganic or organic molecules. The organic-P in cattle, swine, and poultry slurries was 1–15% of the total-P, with the rest being inorganic (as orthophosphate).[321] The proportion of organic-P was 5–15% of the total-P after various manures were stored for two months;

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[316] W.F. Ritter and A.E.M. Chirnside, 1987, "Influence of agricultural practices on nitrates in the water table aquifer," *Biological Wastes*, 19, p. 165; R. Fleming, M. MacAlpine, and C. Tiffin, 1998, *Nitrate Levels in Soil, Tile Drainage Water and Shallow Groundwater under a Variety of Farm Management Systems* (Vancouver, B.C.: CSAE), Paper 98-101.
[317] C. Chang, T.G. Sommerfeldt, and T. Entz, 1991, "Soil chemistry after eleven annual applications of cattle feedlot manure," *Journal of Environmental Quality*, 20, p. 475.
[318] Ontario, Ministry of Agriculture, Food and Rural Affairs (OMAFRA), 1999a, *Field Crop Recommendations 1999–2000,* Publication 296 (Toronto, ON: Queen's Printer), p. 154.
[319] K.A. Smith, R.J. Unwin, and J.H. Williams, 1985, "Experiments on the fertilizer value of animal waste slurries," *Long Term Effects of Sewage Sludge and Farm Slurries Applications*, J.H. Williams et al. (eds.), (New York: Elsevier Science); R.J. Unwin, 1987, "The accumulation of manure-applied phosphorus and potassium in soils," *Journal of the Science of Food and Agriculture*, 40, p. 315.
[320] K.A. Smith and T.A. Van Dijk, 1987, "Utilization of phosphorus and potassium from animal manures on grassland and forage crops," *Animal Manure on Grassland and Fodder Crops: Fertilizer or Waste?*, H.G. Van Der Meer et al. (eds.), (Boston: Martinus Nijhoff).
[321] R.G. Gerritse and R. Vriesema, 1984, "Phosphate distribution in animal waste slurries," *Journal of Agricultural Science*, 102, p. 159.

this was considered to be an end-result equilibrium following microbial transformations.[322] The inorganic-P was present as crystals or precipitates of calcium phosphates. Barnett indicated that the proportions of organic-P and inorganic-P in manure affected the fertilizing value, noting that crop response is directly related to the inorganic-P content.[323] On the other hand, the organic-P fraction (inositols, phospholipids, and nucleic acids) is marginally available but to varying extents.

Barnett also noted that the manures from monogastric animals (swine, poultry) usually contained much more P (22–23 g/kg P dry matter) than those from ruminant animals (cattle, sheep) (4–6 g/kg P dry matter) although there may be large variations in concentration. Only a small part of the organic-P appears to move readily through the soil and is probably of microbial origin, of high molecular weight, and only slightly adsorbed by soils.

Most of the P occurs in feces. Organic-P in the nucleic acid and phytate (inositol) forms can be persistent since mineralization of these forms is a slow process.[324] Van Faassen and Van Dijk argued that the differences in the fertilizing value of manure-P and fertilizer-P cannot be due to the presence of organic-P because it constitutes only 10–20% of the total-P in manure.[325]

The concentration of P in the soil solution is a dynamic function of physical and chemical processes that control the solubility of mineral P, the release of P from organic forms, and the amounts removed by plants and microorganisms.[326] The organic forms of P can be sub-divided into labile and resistant fractions, with the labile fraction tending to remain constant unless severely depleted by mineralization.[327] The maximum amount of P that is present in solution in

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[322] H.G. Van Faassen and H. Van Dijk, 1987, "Manure as a source of nitrogen and phosphorus in soils," *Animal Manure on Grassland and Fodder Crops: Fertilizer or Waste?* H.G. Van der Meer et al. (eds.), (Boston: Martinus Nijhoff).
[323] G.M. Barnett, 1994a, "Phosphorus forms in animal manure," *Bioresource Technology*, 49, p. 139; G.M. Barnett, 1994b, "Manure P fractionation," *Bioresource Technology,* 49, p. 149.
[324] Van Faassen and Van Dijk, 1987.
[325] Ibid.
[326] A.N. Sharpley, S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman, 1992, "The transport of bioavailable phosphorus in agricultural runoff," *Journal of Environmental Quality*, 21, p. 30.
[327] A.N. Sharpley and S.J. Smith, 1985, "Fraction of inorganic and organic phosphorus in virgin and cultivated soils," *Soil Science Society of America Journal*, 49, p. 127.

soil water is related to the natural level of labile-P and how much additional P has been applied as fertilizer in organic and inorganic form.[328]

3.2.7.3 *Metals*

Because copper and zinc are included in feed, considerable amounts can be applied to soil in manure.[329] The Zn content of soil increased in proportion to the amount of manure applied, but the Cu content did not show a significant change.[330] Soil became more acid with the application of cattle manure[331] and pig slurry.[332] Long-term application of pig slurry to grassland was investigated to establish how metals such as copper and zinc from feed additives might affect the soil metal content.[333] Total nickel and the lead content were not increased by slurry application. However, the copper and zinc content of the soil was increased and the availability of the metal to the herbage was enhanced. The application of 200 m^3/ha/y of pig slurry acidified the soil, tending to reduce the soil microbial biomass, but the increase in copper could also have affected the microbial population. The effect of cattle manure was much smaller. Verloo and Willaert concluded that the actual impact of slurry on heavy metal accumulation in soils and in the crops growing on them depended on acidity.[334] Continued application at high rates may

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[328] K.P. Raven and L.R. Hossner, 1993, "Phosphorus desorbtion quantity-intensity relationships in soil," *Soil Science Society of America Journal*, 57, p. 1501; A.N. Sharpley and S.J. Smith, 1989, "Mineralization and leaching of phosphorus from soil incubated with surface-applied and incorporated crop residue," *Journal of Environmental Quality*, 18, p. 101.

[329] A.L. Sutton, D.W. Nelson, V.B. Mayrose, and D.T. Kelly, 1983, "Effect of copper levels in swine manure on corn and soil," *Journal of Environmental Quality*, 12, p. 198.

[330] Chang, Sommerfeldt, and Entz, 1991.

[331] Ibid.

[332] M.P. Bernal, A. Roig, A. Lax, and A.F. Navarro, 1992, "Effects of the application of pig slurry on some physico-chemical and physical properties of calcareous soils," *Bioresource Technology*, 42, p. 233.

[333] P. Christie, 1990 "Accumulation of potentially toxic metals in grassland from long-term slurry application," *Fertilization and the Environment*, R. Merckx, H. Vereecken, and K. Vlassak (eds.), (Leuven, Belgium: Leuven University Press), p. 124.

[334] M. Verloo and G. Willaert, 1990, "Direct and indirect effects of fertilization practices on heavy metals in plants and soils," *Fertilization and the Environment*, R. Merckx, H. Vereecken, and K. Vlassak (eds.), (Leuven, Belgium: Leuven University Press), p. 79.

result in toxic levels of copper in the long term,[335] but this is not likely to occur on neutral to alkaline soils.[336]

Organic matter amendments are thought likely to lead to increases in the water-soluble forms of Zn rather than of Cu, due to the direct effects of the organic matter and dissolved carbon and to indirect effects on other soil properties (e.g., pH and redox status).[337] The application of manure resulted in a decrease in soil pH which, even two months later, was an important factor in the dissolution of weakly bound metals.[338] Thus, even if the water-soluble-Cu content of fresh liquid swine manure is relatively small,[339] application of manure to soil may mobilize some of the Cu and Zn already present from previous applications.[340] The fate of metals in manured soils is related to the fate of organic matter, with little difference due to the type of manure.[341]

3.2.7.4 *Bacteria*

The potential for movement to, and eventual contamination of, water resources by microorganisms depends on their concentration in manure at the time of application and their survival. Manure may affect survival of bacteria: Östling and Lindgren found that 20–40 times more indigenous Bacillus spores were present on manured crops than on un-manured crops, and these numbers

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[335] K. Meeus-Verdinne, G. Neirinckx, X. Monseur, and R. de Borger, 1980, "Real or potential risk of pollution of soil, crops, surface and groundwater due to land spreading of liquid manure," *Effluent from Livestock*, J.K.R. Gasser (ed.), (London: Applied Science), p. 399.

[336] M.A. Anderson, J.R. McKenna, D.C. Martens, S.J. Donohue, S.T. Kornegay, and H.D. Lindemann, 1991, "Long-term effects of copper rich swine manure application on continuous corn production," *Communications in Soil Science and Plant Analysis*, 22, p. 993.

[337] L.M. Shuman, 1991, "Chemical forms of micronutrients in soil," *Micronutrients in Agriculture*, 2nd ed., J.J. Mortvedt, F.R. Cox, L.M. Shuman, and R.M. Welch (eds.), (Madison, WI: Soil Science Society of America). p. 113; P. Del Castilho, W.J. Chardon, and W. Salomons, 1993a, "Influence of cattle-manure slurry application on the solubility of cadmium, copper and zinc in a manured acidic, loamy-sand soil," *Journal of Environmental Quality*, 22, p. 686.

[338] W. Salomons and U. Förstner, 1984, *Metals in the Hydrocycle* (Berlin, New York: Springer-Verlag).

[339] W.P. Miller, D.C. Martens, L.W. Zelazny, and E.T. Kornegay, 1986, "Forms of solid phase copper in copper-enriched swine manure," *Journal of Environmental Quality*, 15, p. 69.

[340] P. Del Castilho, J.W. Dalenberg, K. Brunt, and A.P. Bruins, 1993b, "Dissolved organic matter, cadmium, copper and zinc in pig slurry- and soil solution-size exclusion chromatography fractions," *International Journal of Environmental Analytical Chemistry*, 50, p. 91.

[341] J. Japenga, J.W. Dalenberg, D. Wiersma, S.D. Scheltens, D. Hesterberg, and W. Salomons, 1992, "Effect of liquid animal manure application on the solubilization of heavy metals from soil," *International Journal of Environmental Analytical Chemistry*, 46, p. 25.

remained constant with time to harvest.[342] However, this was not the case for bacteria originating in the manure itself, such as *Clostridium*, some coliforms, and *E. coli*, all of which declined with time after manure application. The survival of any non-indigenous bacteria depends on several factors including soil pH, soil water content, organic matter content, soil texture, temperature, availability of nutrients, adsorption properties of the soil (MacLean found that soils containing clays with a large surface area can adsorb bacteria),[343] and biological interactions in the soil.[344]

Soil fauna can also be highly competitive. Pathogenic bacteria associated with manure may not accumulate in soils containing earthworms. 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 normal bacteria. Free-living protozoa, nematodes, and the soil bacterium *Bdellovibrio* are also predators of bacteria in the soil.[345] Presence of these organisms may reduce or limit bacterial numbers. Nonetheless, introduced bacteria may still be able to survive for an extended period after manure application. On average, 10% of fecal coliforms and fecal streptococci were still present in the soil 11 and 14 days respectively after application of pig manure.[346]

The survival in soil of *E. coli*, including *E. coli* O157:H7, has received particular attention. In cold soils (<5°C) the bacteria can survive for up to 100 days. Survival periods are shorter in coarse-textured soils than in finer-textured soils (figure 3-4). *Campylobacter* species appear to have somewhat shorter survival times. *C. jejuni* survived in soil for at least ten days but this number could double when the ambient temperature decreased to 6°C.[347]

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[342] C.E. Östling and S.E. Lindgren, 1991, "Bacteria in manure and on manured and NPK fertilized silage crops," *Journal of the Science of Food and Agriculture*, 55, p. 579.

[343] A.J. MacLean, 1983, "Pathogens of animals in manure: Environmental impact and public health," *Farm Animal Manures in the Canadian Environment* (Ottawa: National Research Council of Canada Associate Committee on Scientific Criteria for Environmental Quality), p. 103.

[344] J. Abu-Ashour, D.M. Joy, H. Lee, H.R. Whiteley, and S. Zelin, 1994b, "Transport of microorganisms through soil," *Water, Air, & Soil Pollution*, 75, p. 141.

[345] T.C. Peterson and R.C. Ward, 1989, "Development of a bacterial transport model for coarse soils," *Water Resources Bulletin*, 25, p. 349.

[346] D.S. Chandler, I. Farran, and J.S. Craven, 1981, "Persistence and distribution of pollution indicator bacteria on land used for disposal of piggery effluent," *Applied and Environmental Microbiology*, 42, p. 453.

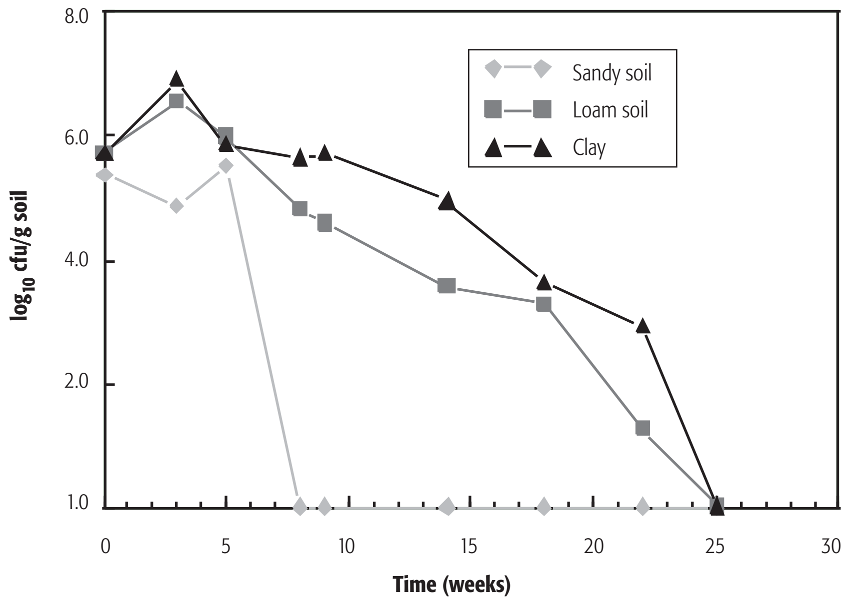
[347] R.W. Lindenstruth and B.Q. Ward, 1948, "Viability of *Vibrio fetus* in hay, soil and manure," *Journal of the American Veterinary Medical Association*, 113, p. 163.

One area of concern is manure from animals routinely treated with antibiotics. Current research in Ontario has failed to identify increased antibiotic resistance in bacteria from fields regularly augmented with this manure.[348] This suggests that, if manure is properly applied, land application does not pose an additional threat to water resources from antibiotic-resistant bacteria.

3.2.7.5 *Viruses*

Viruses near the soil surface are rapidly inactivated by the combination of stresses imposed by sunlight, soil drying, predation, and other soil-based factors such as pH. Kowal reviewed the literature on virus survival.[349] Moisture content appears to be a major factor once the virus has penetrated the soil surface. About 100 days is the longest survival time of enteric viruses.

Figure 3-4 Survival of *E. coli* O157:H7 in Soils of Different Texture



Source: Redrawn from D.R. Fenlon, I.D. Ogden, A. Vinten, and I. Svoboda, 2000, "The fate of *Escherichia coli* and *E. coli* O157 in cattle slurry after application to land," *The Society for Applied Microbiology*, 88, p. 149S.

[348] E. Topp, 2000, [personal communication].

[349] N.E. Kowal, 1985, *Health Effects of Land Application of Municipal Sludge* (Triangle Park, NC: Health Effects Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency).

The movement of viruses from manure in surface runoff has not received significant attention. Movement to groundwater has been investigated in model systems or has been inferred from studies on wastewater application. Penetration of virus particles was deeper in sandy soil (with movement to 17.4 m) than in loamy or clay soils. It was also greater under conditions of saturated flow than under unsaturated flow.[350]

3.2.7.6 *Endocrine-disruptive compounds*

The fate of estradiol-17β excreted onto Kentucky bluegrass bedding by mares between 12 and 16 weeks gestation was investigated by Busheé et al.[351] The concentration of estradiol-17β was 35.1 μg/kg in the bedding, almost 7 times greater than the value found in municipal sewage sludge (5.2 μg/kg). However, the water content of the sewage sludge (80%) was much greater than that of the bedding (7%), so on a dry-weight basis the differences were much less (40 μg/kg and 30 μg/kg, respectively). The bedding material was applied to a tall fescue pasture at a rate of 9.1 t/ha, providing an equivalent of approximately 100 kg/ha N. The pasture was then irrigated to generate runoff. The average concentration of estradiol-17β in the runoff (adjusted for flow) was 0.6 μg/L. In a similar experiment, litter from a broiler chicken barn was applied at rates of 1.76–7.05 t/ha.[352] The estradiol-17β concentration in the litter was 131 μg/kg (dry-weight basis). Concentrations of estradiol-17β in runoff ranged from 0.2 to 1.3 μg/L. Pretreatment with alum (aluminium sulphate) increased the acidity of the manure and reduced the concentration of estradiol-17β in runoff from the poultry litter by 40%, but had no effect on the hormone in the horse bedding runoff, perhaps because of inadequate mixing.

Once incorporated into the soil, natural hormones in the manure do not appear to persist. They may be readily broken down by soil microbes,[353] but Shore et al.

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350 J.C. Lance and C.P. Gerba, 1984, "Virus movement in soil during saturated and unsaturated flow," *Applied and Environmental Microbiology*, 47, p. 335; J.C. Lance, C.P. Gerba, and D.S. Wang, 1982, "Comparative movement of different enteroviruses in soil columns," *Journal of Environmental Quality*, 11, p. 347.

351 E.L. Busheé, D.R. Edwards, and P.A. Moore, 1998, "Quality of runoff from plots treated with municipal sludge and horse bedding," *Transactions of the American Society of Agricultural Engineers*, 41, p. 1035.

352 D.J. Nichols, T.C. Daniel, P.A. Moore, D.R. Edwards, and D.H. Pote, 1997, "Runoff of estrogen hormone 17-Estradiol from poultry litter applied to pasture," *Journal of Environmental Quality*, 26, p. 1002.

353 Topp, 2000.

suggested that physicochemical processes were important.[354] However, five months after the application of manure from broiler chickens containing 0.03 μg/g testosterone and 0.03 μg/g estrogen, no estrogen could be identified in soil to which manure had been applied 5 months earlier, but testosterone was present.[355]

3.2.7.7 *Summary*

Some of the NH_4^+ in manure can be taken up directly by the crop or may be nitrified to the much more mobile NO_3^- form, which can also be used by the crop. The aim of the producer is to have the crop remove as much of these mineral-N forms as possible from the soil. Some of the NO_3^- may undergo denitrification to N_2O or even N_2 gas. The additional organic carbon applied in manure increases the likelihood of N being lost by denitrification. However, NO_3^- in the soil is at risk of leaching when rainfall exceeds the transpiration of water by the crop and evaporation from the soil.

The P content of manure can be in mineral or organic form. In liquid manure the larger fraction is in mineral form. The amount of P available to a crop in the year of application is still in dispute, but over successive years, all eventually becomes available. Much of the P applied is found as crystals or precipitates, so is largely immobile within the soil profile.

Cu and Zn tend to accumulate in soils given regular applications of manure. Acidification of the soil tends to increase their mobility, but in Ontario's calcareous soils this is not considered a major threat to water resources.

Bacteria can survive longer in cold soils than in warm soils, and longer in fine-textured than in coarse-textured soils. Biological as well as physical factors influence the survival. There is no evidence that bacteria in soils subject to regular manure applications have developed more antibiotic resistance because of the feeding of subtherapeutic antibiotic doses to enhance growth of livestock and poultry.

Estrogenic endocrine-disrupting compounds in manure do not appear to persist in soil.

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[354] Shore, Correll, and Chakraborty, 1995.
[355] Ibid.

3.2.8 Contamination of water resources

The majority of research to date has failed to quantify the maximum manure loading that does not cause a negative environmental impact. For example, an application of 36,000 L/ha of manure had a more deleterious impact on water quality than did an application of 140,700 L/ha.[356]

3.2.8.1 *Nitrate*

There is little information available for Ontario on the impact of manure application on nitrate leaching. In part this is because the potential for animal manure to contaminate groundwater with nitrate is difficult to determine due to:

- the possible losses by NH_3 volatilization,
- the need for the ammoniacal and organic forms of nitrogen to be converted to the more mobile NO_3^- form, and
- the other possible transformations of NO_3^-.

For example, after a heavy application of slurry to light-textured soil, a significant amount could not be accounted for in either the soil or drainage water.[357] The nitrate in the drainage water was less than 1% of the total N applied. Nonetheless, the average nitrate concentrations in tile-drainage water from land receiving swine manure was 26.5 mg/L N (from five swine farms), significantly greater than the 13.8 mg/L N measured for 15 cash-crop farms.[358] Nitrate levels in the shallow groundwater were also significantly higher for manured fields (5.77 mg/L N) compared with non-manured fields (2.46 mg/L N). One reason for greater nitrate leaching from manured land than from land on which mineral fertilizer is applied could be that producers make no allowance for the mineralization of the organic nitrogen in the manure.[359]

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[356] D.M. Dean and M.E. Foran, 1991, *The Effect of Farm Liquid Waste Application on Receiving Water Quality. Final Report RAC Projects 430G and 512G* (Exeter, ON: Ausable-Bayfield Conservation Authority).
[357] Burford, Greenland, and Pain, 1976.
[358] Fleming, MacAlpine, and Tiffin, 1998.
[359] I.K. Thomsen, J.F. Hansen, V. Kjellerup, and B.T. Christensen, 1993, "Effects of cropping system and rates of nitrogen in animal slurry and mineral fertilizer on nitrate leaching from a sandy loam," *Soil Use and Management*, 9, p. 53.

The changes in soil structure resulting from reduced tillage may modify significantly the impacts of agricultural practices on the environment. In particular, the consequences for manure application need to be considered. The reduction in air-filled porosity can limit the volume of liquid manure that could be applied without inducing drain flow because of a greater likelihood of transport through macropores. Consequently, the potential for nitrate contamination of groundwater and bacterial contamination of rivers could increase.[360] However, Beven and Germann suggested that macropores do not always increase infiltration because water may move from these pores into the soil matrix, but at a slightly deeper depth in the soil rather than at the soil surface.[361]

3.2.8.2 *Phosphorus*

Some 10 years ago, phosphorus contribution to surface water in runoff from agricultural land was the major focus of the Federal-Provincial Soil and Water Environmental Enhancement Program (SWEEP). Studies during the 1970s under the Pollution from Land Use Activities Reference Group (PLUARG) of the International Joint Commission for the Great Lakes (IJC) showed that runoff from agricultural land was responsible for about 70% of the phosphorus reaching Lake Erie from the tributaries in Ontario.[362] About 20% of this amount (15% of the total) was estimated to be due to direct inputs from livestock operations, including runoff from storage areas and surface runoff from manure applied close to streams and not incorporated. The remainder was due largely to phosphorus associated with eroded sediment. Manure application may have two opposing effects on this latter contribution: it increases the P-content of the soil and hence the concentration on the eroded sediment, while on the other hand manure tends to improve soil structure and hence reduce erosion.

One poorly understood aspect of phosphorus in runoff is the bioavailability of different forms of phosphorus.[363] While manure application may not increase the total phosphorus in runoff, it may increase the amount of bioavailable

[360] Dean and Foran, 1991.
[361] K. Beven and P. Germann, 1982, "Macropores and water flow in soils," *Water Resources Research*, 18, p. 1311.
[362] M.H. Miller, J.B. Robinson, D.R. Coote, A.C. Spires, and D.W. Draper, 1982, "Agriculture and water quality in the Canadian Great Lakes Basin: III. Phosphorus," *Journal of Environmental Quality*, 11, p. 487.
[363] Sharpley et al., 1992

phosphorus. In Delaware, continual land application of animal manures has resulted in an accumulation of P in the surface soil.[364] These authors concluded that the bioavailability of P in runoff water from land following manure application increased because of the increased transport of low-density organic material together with the high solubility of manure-P. The magnitude of the increase would be expected to vary, depending on the density of the manure, the water, and P-content, for different animal sources.[365] There is some evidence that P in the manure from animals fed HAP corn (see section 3.2.1) is more bioavailable than that from conventionally fed animals.[366]

Although the phosphorus leaching is considered less important than the leaching of nitrate, particularly with respect to water resources used for drinking water supplies, the right combination of agricultural management practices, soil properties, and climatic conditions can lead to significant losses of soluble- and particulate-P through leaching.[367]

3.2.8.3 *Bacteria*

The Ontario Farm Groundwater Quality Survey found that the proportion of wells contaminated with bacteria was significantly greater on farms where manure was spread than where only mineral fertilizers were used.[368] Soil type was important in this result: less contamination resulted under coarse, gravelly soils and fine-textured soils than under loams.[369] The results of the Ontario Farm Groundwater Quality Survey showed that contamination of drinking-water wells was similar to that under fields where the farmers were carrying out their normal cropping practices.[370] This clearly indicated that groundwater could be contaminated by bacteria moving through the soil, rather than by surface water entering poorly-maintained wells. Evidence of repeated

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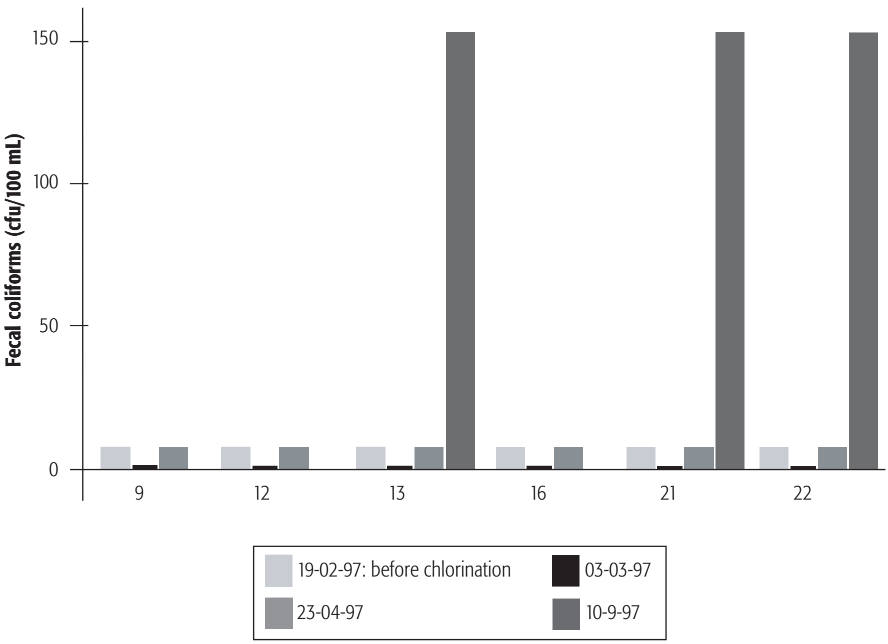
[364] A.N. Sharpley and A.D. Halvorson, 1994, "The management of soil phosphorus availability and its impact on surface water quality," *Advances in Soil Science: Soil Processes and Water Quality*, R. Lal and B.A. Stewart (eds.), (Boca Raton, FL: CRC Press), p. 7.
[365] Ibid.
[366] J.S. Paschold, B.J. Wienhold, and R. Ferguson, 2000, "Crop utilization of N and P from soils receiving manure from swine fed low phytate and traditional corn diets," *Annual Meeting Abstracts, ASA, CSSA, SSSA,* Minneapolis, Minnesota, Nov. 5–9, p. 352.
[367] J.T. Sims, R.R. Simard, and B.C. Joern, 1998, "Phosphorus loss in agricultural drainage: Historical perspective and current research," *Journal of Environmental Quality*, 27, p. 277.
[368] Rudolph, Barry, and Goss, 1998.
[369] Goss, Barry, and Rudolph, 1998.
[370] Rudolph, Barry, and Goss, 1998.

groundwater contamination has been observed under land where manure was regularly applied (figure 3-5).

Liquid manure adversely affected tile-water quality when applied to the land following the current farming guidelines. Of the manure spreading events investigated, 75% resulted in water quality impairment.[371] Bacteriological contamination from tile drains can be greater after injection than after surface spreading.[372] It is difficult to determine an acceptable rate of liquid manure application, due to the numerous factors which affect the contamination of watercourses.[373] The importance of soil macropores for the rapid transport of bacteria to tile drains was highlighted in their studies.

The likelihood of bacteria moving into water resources declines with time after manure application because the organisms die off, but this takes longer in manure applied in late fall, shortly before freeze-up. Application as a side-dressing for corn (which generally occurs in mid-June, when soils are relatively

Figure 3-5 Presence of Fecal Coliforms in Test Wells



Source: Goss and Unc, unpublished.

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[371] Dean and Foran, 1991.
[372] Ibid.
[373] Foran, Dean, and Taylor, 1993.

dry and warm) results in the shortest period of survival. Later applications might further reduce the likelihood of bacterial contamination, but increase the risk of nitrate contamination of groundwater because the crop has insufficient time to acquire the nutrient from the soil.

Thelin and Gifford showed that if a sample of freshly voided manure was subject to water from a rainfall simulator within 5 days, the concentration of fecal coliform bacteria in runoff was in the order of 10^4/mL, but this number declined to 400/mL after 30 days.[374]

3.2.8.4 *Endocrine-disruptive compounds*

Most studies have only reported the transport of the natural hormones from manure in surface runoff. The most detailed investigation[375] showed that the concentration of estradiol-17β (y μg/L) in runoff was related to the rate of broiler chicken litter application rate (x t/ha) by the equation:

$$y = -0.0096 + 0.1674x \qquad (1)$$

The concentration of estradiol-17β in runoff from litter left on the surface for 7 days was only 10% of that from the freshly applied litter. Shore et al. reported that surface runoff from fields receiving broiler chicken manure contained 14 to 20 ng/L estrogen and 0.9 to 34.2 ng/L testosterone.[376] Levels of natural hormones above 10 ng/L in water can have measurable effects on both plants and animals.[377]

Servos et al. reported the detection of endocrine-disruptive compounds in tile-drainage water, indicating that they may also be moving directly into the tile drains through preferential flow paths.[378]

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[374] R. Thelin and G.F. Gifford, 1983, "Fecal coliform release patterns from fecal material of cattle," *Journal of Environmental Quality*, 12, p. 57.
[375] Nichols et al., 1997.
[376] Shore, Correll, and Chakraborty, 1995.
[377] Ibid.
[378] M. Servos, K. Burnison, S. Brown, T. Mayer, J. Sherry, M. McMaster, G. Van Der Kraak, R. McInnis, J. Toito, A. Jurkovic, D. Nuttley, T. Neheli, M. Villella, T. Ternes, E. Topp, and P. Chambers, 1998, "Runoff of estrogens into small streams after application of hog manure to agricultural fields in southern Ontario," *19th Annual Meeting of the Society of Environmental Toxicology and Chemistry*, Charlotte, NC, Nov. 15–19.

Estrogens may bind to soil more readily than testosterone and in consequence may be more likely to leave manured field in surface runoff. Testosterone may be more readily leached, and may explain the presence of at least ten-times more testosterone (1 ng/L) than estrogen (<0.1 ng/L) in water from a well on a farm applying chicken manure to the land.[379]

3.2.8.5 *Summary*

Little information is available for Ontario on the impact of manure application on nitrate leaching. Nitrate leaching can be greater from manured land than from land receiving mineral fertilizer. However, this could be because producers are uncertain about making any allowance for the mineralization of the organic nitrogen in the manure. Tillage may affect the potential for leaching of NO_3^-, resulting in greater losses with no-till, but evidence is lacking for Ontario.

Manure applications increase the P-content of the soil and hence the concentration on the eroded sediment. However, manure also tends to improve soil structure and hence reduce erosion.

A major problem is associated with applying manure to land with tile drains. After liquid manure application, bacteria move rapidly to the tile drains if the soil is close to field capacity.

The likelihood of bacteria moving into water resources declines with time because the organisms die off. The shortest period of survival would be expected for bacteria in the summer-applied manure. However, manure applications later than the time of side-dressing for corn might reduce the likelihood of bacterial contamination, but increase the risk of nitrate contamination of groundwater.

Endocrine-disruptive compounds are found in runoff from land with manure on the surface as well as in tile-drain discharge, and at concentrations that are considered appreciable.

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[379] Shore, Correll, and Chakraborty, 1995.

3.3 Transport Processes

Substances in manure move to water resources by a variety of transport processes, reviewed in this section.[380] Contaminants originating in manure that affect water resources can be divided into three basic classes:

- simple inorganic ions (e.g., NH_4^+, NO_3^-, $H_2PO_4^+$),
- more complex organic molecules (e.g., phytates and endocrine-disrupting substances), and
- particulates (e.g., microorganisms).

The concentration of simple inorganic ions is controlled by the equilibrium between the solids and their solution phases in soil water. This may involve the formation of sparingly soluble precipitates and adsorption reactions with soil particles. For organic molecules and some inorganic species such as NH_4^+, the final concentration of contaminants in soil water depends on their vapour pressure and their solubility in water and in soil organic matter. In contrast, particulates are generally affected by surface charge. In all cases, transport varies greatly depending on soil structure, especially the size distribution and continuity of soil pores. For inorganic nitrogen compounds and bacteria, the soil is itself a source and may also contain one or more sinks.

3.3.1 Water partitioning at the soil surface

As water is the primary factor determining the movement of contaminants, its partitioning at the soil surface into runoff and infiltration (drainage) is of fundamental importance. During precipitation (rainfall or irrigation), the surface of the soil becomes wet and water starts to move down through the soil. If the rate of precipitation exceeds the ability of the soil to transmit water to its depths, ponding occurs. Ponding allows water to fill very large pores at the soil surface, therefore promoting preferential flow (flow in areas of the soil that offer the least resistance – see section 3.3.4). On land with any slope, the depth of ponding is likely to be very small before the water starts to flow down the slope. The rate of flow of surface runoff can be slowed by crop residues and soil clods. As the flow

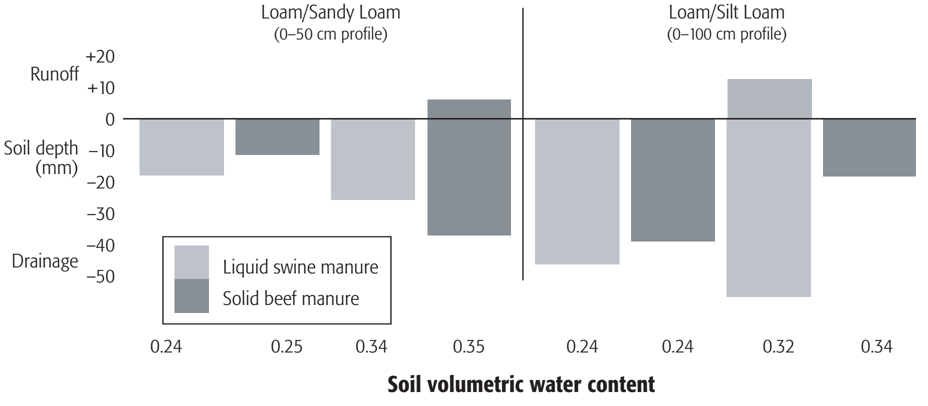
[380] For comprehensive reviews of solute transport, readers are referred to T.M. Addiscott and R.J. Wagenet, 1985, "Concepts of solute leaching in soils: A review of modelling approaches, " *Journal of Soil Science*, 36, p. 411; and N.J. Jarvis, P.E. Jansson, P.E. Dik, and I. Messing, 1991, "Modelling water and solute transport in macroporous soil. I. Model descriptions and sensitivity analysis," *Journal of Soil Science*, 42, p. 59.

slows, the depth of water increases or the ponded area gets larger. In either case it enhances infiltration into the soil and restricts transport off the field.

Increased infiltration into vegetated buffer strips also increases their efficiency of contaminant removal from surface runoff.[381] All fecal coliform bacteria were removed by passage through a 6.1-m vegetated buffer strip, although concentrations of sediment, organic-N, NH_4^+-N, and ortho-phosphate were reduced by only about 70%. Preferential infiltration by the bacteria was cited as the reason for the difference.[382]

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 coarse-textured soils, there is no effect because rainfall intensity is not likely to exceed the infiltration rate. In loamy and finer-textured soils, the application of dilute liquid manure can both encourage surface runoff and enhance

Figure 3-6 Partitioning of Precipitation into Surface Runoff and Drainage after the Application of Liquid Swine or Solid Beef Manure



Note: In general, the application of liquid manure resulted in more drainage than did solid manure. In the finer-textured material, liquid manure also promoted more surface runoff.

Source: After A. Unc and M.J. Goss, 2000, "Effect of manure application on soil properties relevant to bacterial transport," Paper presented at the ASA, CSSA, SSSA Annual Meetings, 5–9 Nov 2000, Minneapolis, Minnesota (Madison, WI: American Society of Agronomy).

[381] M.S. Coyne, R.A. Gilfillen, A. Villalba, Z. Zhang, R. Rhodes, L. Dunn, and R.L. Blevins, 1998, "Fecal bacteria trapping by grass filter strips during simulated rain," *Journal of Soil and Water Conservation*, 53, p. 140.

[382] T.T. Lim, D.R. Edwards, S.R. Workman, B.T. Larson, and L. Dunn, 1998, "Vegetated filter strip removal of cattle manure constituents in runoff," *Transactions of the American Society of Agricultural Engineers*, 41, p. 1375.

preferential flow. Until solid manure has been incorporated, it acts as a mulch and encourages infiltration rather than surface runoff (figure 3-6).

3.3.1.1 *Summary*

Conditions at the soil surface affect the partitioning between surface runoff and drainage. Liquid manure appears to encourage the development of surface runoff, whereas solid manure encourages drainage. Preferential flow paths are important for rapid transport.

3.3.2 Basic equations governing transport through the soil

Water movement through the unsaturated zone toward an aquifer can be described by the Richards equation, assuming one-dimensional flow in a homogeneous soil:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta\varphi}{\delta z}\right] - U(z,t) \qquad (2)$$

where

θ = volumetric water content
$K(\theta)$ = the water content-dependent hydraulic conductivity
$\delta\varphi\delta z$ = the hydraulic gradient
U = a sink term covering extraction or uptake of water by plant roots
z = depth, taken as positive downwards
t = time

To develop a solvable form of the equation, a term called the hydraulic diffusivity, D (2), is introduced, defined as:

$$D(\theta) = K(\theta)\frac{\delta\varphi}{\delta\theta} \qquad (3)$$

where

φ = the matric potential
$\delta\varphi/\delta\theta$ = the slope of the moisture release characteristic curve.

Equation 2 becomes:

$$\frac{\delta\varphi}{\delta t} = \frac{\delta}{\delta z}\left[D(\theta)\left(\frac{\delta\theta}{\delta z}\right) - K(\theta)\right] - U(z,t) \qquad (4)$$

A quantitative description of the transport of contaminants that only dissolve in water usually assumes the convection-dispersion equation (CDE):

$$q_s = q_w C_l - D_e \frac{dC_l}{dz} - D_h \frac{dC_l}{dz} \qquad (5)$$

where

q_s = the mass of the solute moving through unit-cross-sectional area per unit time
C_l = the concentration of the solute in the soil water
D_e = the effective diffusion coefficient of the solute in the soil, adjusted for the water content and tortuosity of the pore system
D_h = the mechanical dispersion coefficient that includes the effect of local variation in the velocity of water in large and small pores
q_w = the water flux density

Thus, the transport of contaminants depends on factors governing their concentration in the soil solution and the flux of water available to move them. If a contaminant undergoes transformations in the soil, is subject to die-off, or is absorbed by plants, additional sink terms have to be added to the continuity equation, as in equation 2. Further refinements are needed to include exchange of a contaminant between the liquid and solid phases in the soil.

3.3.2.1 *Summary*

Basic equations, which describe the movement of water and pollutants through soil, highlight the importance of the concentration of a potential contaminant in the soil solution and the amount of water available to move it. To provide an adequate description of the movement, knowledge is needed of other sources of the contaminant in the soil, any potential sinks, and factors affecting its survival.

3.3.3 Contaminant characteristics relevant to their transport

It is important to consider the features of different contaminants that affect their transport. Nitrate travels in solution with infiltrating water. Plant uptake and denitrification remove nitrate from solution, but these processes are likely less important when infiltration is rapid. Once nitrate enters a preferential flow path, there is little chance of it being removed from solution. In contrast, NH_4^+ and $H_2PO_4^+$ can be removed from the water through interaction with the soil matrix.

Volatile organic compounds can also move as vapours, so additional terms must be added in the equations given in section 3.3.2 to take account of the diffusive and dispersive fluxes in this phase. Although NH_3 can form from NH_4^+ and then be lost by volatilization, it may also move in the gaseous phase within the soil. As already described, much of the ammoniacal nitrogen present in the manure shortly after excretion may be lost to the atmosphere before field application. Another feature is the variation in N-deposition from the atmosphere. The considerable variation between monitoring sites observed in studies of N-deposition from the atmosphere[383] may be due to the impact of ammonia volatilization from livestock operations.[384]

Transport of particulates such as microorganisms follows that of colloids, although viruses exhibit little filtration and are adsorbed onto low-molecular-weight organic molecules in soil.[385] It is reasonable to assume that the concentration of a solute will tend to become uniformly distributed within each pore space, but this may not be true of colloids. Bacteria are much larger than nitrate ions and their movement is more likely to be affected by the flow associated with the pore size in which they are transported. They have variable surface charge which allows stronger adsorption of the bacteria to soil particles. Bacteria also have very large surface-area-to-volume ratios that provide a large proportion of sites for adsorption. A third consideration with microorganisms is that their populations are dynamic. They are alive and influenced by factors that affect their survival. Many are also motile.

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[383] D.A.J. Barry, D. Goorahoo, and M.J. Goss, 1993, "Estimation of nitrate concentration in groundwater using a whole farm nitrogen budget," *Journal of Environmental Quality*, 22, p. 767.
[384] M.J. Goss, E.G. Beauchamp, and M.H. Miller, 1995b, "Can a farming systems approach help minimize nitrogen losses to the environment?" *Journal of Contaminant Hydrology*, 20, p. 285.
[385] Kowal, 1985.

3.3.3.1 *Summary*

It is not sufficient to describe the transport of contaminants in the water phase without first identifying other factors that can affect mobility.

3.3.4 Preferential flow and solute transport

Soil pore characteristics are important for transport. However, the transport of contaminants in soils with strongly aggregated structures or with large and continuous pores is not well described by models based on equation 5, because preferential flow occurs.[386]

Preferential flow is the process whereby water, and materials contained in it, move by preferred pathways through a porous medium. This means that part of the matrix is effectively bypassed. The term preferential flow does not itself convey a mechanism for the process,[387] whereas the often-used "macropore flow" implies transport through relatively large pores, channels, fissures, or other semi-continuous voids within the soil. Although there is no standardized definition for macropores, some pore classification has been proposed. Luxmoore suggested the classes of micro-, meso-, and macropore, defined by equivalent pore diameters of less than 10 μm, 10 to 1000 μm, and more than 1000 μm (1 mm), respectively.[388] Skopp defined macroporosity as that pore space which provides preferential paths of flow so that mixing and transfer between such pores and the remaining pore space is limited.[389] Some other classifications of soil pore size and their functions with respect to water movement or root penetration have been summarized by Helling and Gish.[390] Pore size and the corresponding capillary potential was given by Beven and Germann.[391]

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[386] G.W. Thomas and R.E. Phillips, 1979, "Consequences of water movement in macropores," *Journal of Environmental Quality*, 8, p. 149; R.J. Wagenet, 1990, "Quantitative prediction of the leaching of organic and inorganic solutes in soil," *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences*, 329, p. 321.
[387] C.S. Helling and T.J. Gish, 1991, "Physical and chemical processes affecting preferential flow," *Preferential Flow*, T.J. Gish and A. Shrimohammadi (eds.), (St. Joseph, MI: American Society of Agricultural Engineers), p. 77.
[388] R.J. Luxmoore, 1981, "Micro-, meso-, and macroporosity of soil," *Soil Science Society of America Journal*, 45, p. 671.
[389] J. Skopp, 1981, "Comment on 'Micro-, meso-, and macroporosity of soil,'" *Soil Science Society of America Journal*, 45, p. 1246.
[390] Helling and Gish, 1991.
[391] Beven and Germann, 1982.

Macropores may develop by physical (e.g., swell-shrink, freeze-thaw, or tillage) or biological (e.g., burrowing by earthworms, insects, and other soil fauna or the growth of roots) processes in the soil. Continuous macropores can be formed by the activity of soil macro-fauna, especially earthworms.[392] In soils with significant swell-shrink behaviour, cracking may be important in the development of a preferential flow domain, and the extent of crack development is generally related to water extraction by roots. The channels created by roots can also dominate the transport process once the original roots have decayed.[393] 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 macropores therefore provide a rapid conduit between the field and the surface water body into which the tile drains discharge. Macropore flow allowed manure liquids to move into subsurface drains within an hour after application.[394]

The essential feature of preferential flow is that percolating water can bypass a large fraction of the soil matrix, thus moving deeper and with less displacement of the initial soil solution than would have been predicted by piston displacement.[395] Watson and Luxmoore found that under ponded conditions, 73% of the flux was conducted through macropores (pore diam. >1 mm).[396] Furthermore, they estimated that 96% of the water was transmitted through only 0.32% of the soil volume. As much as 70–90% of applied chemicals may be moving preferentially through macropores.[397]

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[392] W. Ehlers, 1975, "Observations on earthworm channels and infiltration on tilled and untilled loess soil," *Soil Science*, 119, p. 242.

[393] K.P. Barley, 1954, "Effects of root growth and decay on the permeability of a synthetic sandy loam," *Soil Science*, 78, p. 205.

[394] Fleming and Bradshaw, 1991, 1992a, 1992b.

[395] Beven and Germann, 1982; J. Bouma, 1981, "Soil morphology and preferential flow along macropores," *Agricultural Water Management*, 3, p. 235; V.L. Quisenberry and R.E. Phillips, 1976, "Percolation of surface-applied water in the field," *Soil Science Society of America Journal*, 40, p. 484; V.L. Quisenberry and R.E. Phillips, 1978, "Displacement of soil water by simulated rainfall," *Soil Science Society of America Journal*, 42, p. 675; V.L. Quisenberry, B.R. Smith, R.E. Phillips, H.D. Scott, and S. Nortcliff, 1993, "A soil classification system for describing water and chemical transport," *Soil Science*, 156, p. 306; A. Shirmohammadi, T.J. Gish, A. Sadeghi, and D.A. Lehman, 1991, "Theoretical representation of flow through soils considering macropore effect," *Preferential Flow*, T.J. Gish and A. Shirmohammadi (eds.), (St Joseph, MI: American Society of Agricultural Engineers), p. 233.

[396] K.W. Watson and R.J. Luxmoore, 1986, "Estimating macroporosity in a forest watershed by use of a tension infiltrometer," *Soil Science Society of America Journal.*, 50, p. 578.

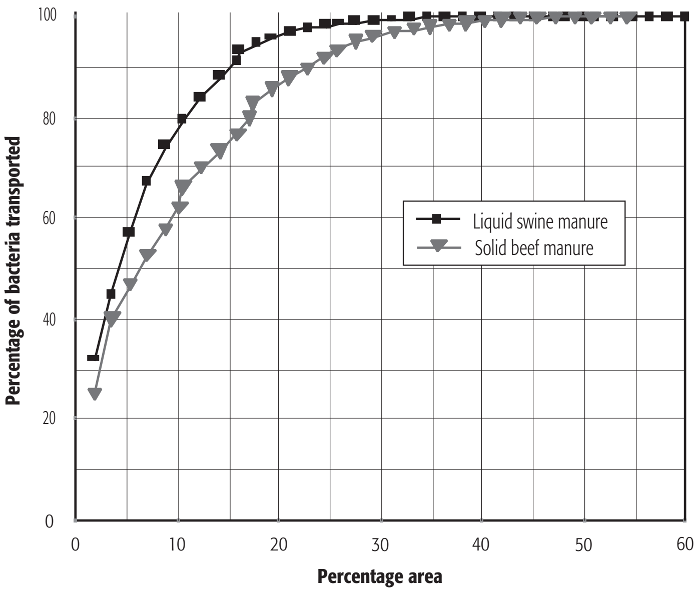
[397] L.R. Ahuja, B.B. Barnes, and K.W. Rojas, 1993, "Characterization of macropore transport studied with the ARS root zone water quality model," *Transactions of the American Society of Agricultural Engineers*, 36, p. 396.

Preferential flow may occur even in coarse-textured soils that are considered to be homogeneous.[398] Macropore flow commenced at the tilled-untilled boundary in a cultivated Maury silt loam[399] and in a Cecil sandy clay loam in the Piedmont of South Carolina.[400]

Transport of bacteria is concentrated in regions of preferential flow. Unc and Goss applied liquid swine manure to an undisturbed column of clay-loam soil.[401] They found that about 90% of bacteria moved through only 15% of the available cross-sectional area. The same proportion from solid beef manure were transported through less than 25% of the cross-sectional area of soil (figure 3-7).

Jardine et al. found that solutes were transported by convection and diffusion from small-pore to large-pore regions in undisturbed soil as a result of hydraulic and

Figure 3-7 Evidence for Preferential Movement of *E. coli* Bacteria from Manure Applied to a Column of Clay-loam Soil



Source: Unc and Goss, 2000.

[398] K.J.S. Kung and S.V. Donohue, 1991, "Improved solute-sampling protocol in a sandy vadose zone using ground-penetrating radar," *Soil Science Society of America Journal*, 55, p. 1543; M.S. Andreini, J.-Y. Parlange, and T.S.Steenhuis, 1990, "A numerical model for preferential solute movement in structured soils," *Geoderma*, 46, p. 193.
[399] Quisenberry and Phillips, 1976.
[400] W.A. Hatfield, 1988, *Water and Anion Movement in a Typic Hapludult*, Ph.D. dissertation, Clemson Univ. Clemson, SC.

concentration gradients, respectively.[402] Small pores were a major source of the solute transported rapidly by large pores. A diffusion-based mechanism described by Luxmoore,[403] in which new water entering a soil gains the chemical attributes of old water, could explain the results reported by Jardine et al.[404] According to Luxmoore, a large surface area of interaction, combined with a short diffusion path between mesopore channels and micropores, allows diffusion to be a significant contributor to chemical transport during preferential flow events.[405]

Whether macropore flow increases or decreases, the residence time of solutes in soil, including those in manure, depends on the location of solutes relative to the macropores.[406] However, macropore flow has been shown to be a major factor in groundwater contamination. For example, leaching of nitrate added to the soil surface as fertilizer was more rapid than leaching of nitrate formed by mineralization of organic matter within soil aggregates.[407]

The rainfall pattern after manure application is critical for the subsequent movement of solutes. An initial small rain (5–10 mm) may move the solute into the soil matrix, thereby reducing the potential for transport in macropores during subsequent rainfall events.[408]

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[401] A. Unc and M.J. Goss, 2000, "Effect of manure application on soil properties relevant to bacterial transport," Paper presented at the *ASA, CSSA, SSSA Annual Meetings*, 5–9 Nov. 2000, Minneapolis, Minnesota (Madison, WI: American Society of Agronomy).
[402] P.M. Jardine, G.V. Wilson, and R.J. Luxmoore, 1990, "Unsaturated solute transport through a forest soil during rain storm events," *Geoderma*, 46, p. 103.
[403] R.J. Luxmoore, 1991, "On preferential flow and its measurement," *Preferential Flow*, T.J. Gish and A. Shrimohammadi (eds.), (St. Joseph, MI: American Society of Agricultural Engineers), p. 113.
[404] Jardine, Wilson, and Luxmoore, 1990.
[405] Luxmoore, 1991.
[406] A. Wild, 1972, "Nitrate leaching under bare fallow at a site in northern Nigeria," *J. Soil Science*, 23, p. 315; D.R. Edwards, V.W. Benson, J.R. Williams, T.C. Daniel, J. Lemunyon, and R.G. Gilbert, 1994, "Use of the EPIC model to predict runoff transport of surface-applied inorganic fertilizer and poultry manure constituents," *Transactions of the American Society of Agricultural Engineers*, 37, p. 403; S. Chen, R.E. Franklin, and A.D. Johnson, 1997, "Clay film effects on ion transport in soil," *Soil Science*, 162, p. 91; S. Chen, R.E. Franklin, V. Quisenberry, and P. Dang, 1999, "The effect of preferential flow on the short and long-term spatial distribution of surface applied solutes in a structured soil," *Geoderma*, 90, p. 229.
[407] Wild, 1972; M.J. Goss, P. Colbourn, G.L. Harris, and K.R. Howse, 1987, "Leaching of nitrogen under autumn-sown crops and the effects of tillage," *Nitrogen Efficiency in Agricultural Soils. EEC Seminar*, D. S. Jenkinson and K. A. Smith (eds.), Edinburgh, September 1987 (London: Elsevier Applied Science), p. 269.
[408] M.J. Shipitalo, W.M. Edwards, W.A. Dock, and L.B. Owens, 1990, "Initial storm effects on macropore transport of surface-applied chemicals in no-till soil," *Soil Science Society of America Journal*, 54, p. 1530; M.H. Golabi, D.E. Radcliffe, W.L. Hargrove, and E.W. Tollner, 1995, "Macro effects in conventional tillage and no-tillage soils," *Journal of Soil and Water Conservation*, 50, p. 205.

The initial location of potential contaminants in the soil may affect their movement.[409] Materials at the soil surface may move into macropores open at the soil surface, and then downward through the topsoil and subsoil to the water table. However, material that has been incorporated into large soil aggregates within the topsoil may be protected from being leached by macropores because most water will move in these pores and bypass the aggregates rather than move through them.

Initial soil moisture content and rainfall intensity and duration may affect solute distribution and movement among small and large pores.[410] During high rainfall intensity (when water application exceeds the soil infiltration rate) or under conditions of saturated flow, preferential flow can be initiated. Soil morphology,[411] clay films,[412] and surface condition[413] affect water and solute distribution or transport. Among these factors, those related to pedogenetic processes, such as soil morphology and structure, require longer time periods to show effects. Other factors such as moisture content, tillage, and cultural practices may be relatively transient in their effect. Understanding the effects of these factors on water and solute transport may ultimately lead to a more reliable prediction of transport processes in soil[414] including the movement of contaminants.[415]

Helling and Gish described some factors affecting the process of preferential flow, including soil porosity, pore characteristics, structure, initial moisture content, and soil management.[416] Flow through tubes is proportional to the fourth power of their radii, therefore drainage is much more rapid through large continuous macropores than through pores of smaller diameter. Mouldboard ploughing may destroy the continuity of pores between the plough layer and the deep horizons. Long-term no-tillage plots, on the other hand, often develop a high density of continuous, relatively large vertical channels.[417] Manure application may

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[409] Jardine, Wilson, and Luxmoore, 1990; Shipitalo et al., 1990; D.J. Timlin, G.C. Heathman, and L.R. Ahuja, 1992, "Solute leaching in crop row vs. interrow zones," *Soil Science Society of America Journal*, 56, p. 384; Golabi et al., 1995; Chen, Franklin, and Johnson, 1997; Chen et al., 1999.
[410] Jardine, Wilson, and Luxmoore, 1990.
[411] Bouma, 1981.
[412] Quisenberry et al., 1993; Chen, Franklin, and Johnson, 1997.
[413] R.E. Phillips, V.L. Quisenberry, J.M. Zeleznik, and G.H. Dunn, 1989, "Mechanism of water entry into simulated macropore," *Soil Science Society of America Journal*, 53, p. 1629; Quisenberry et al., 1993.
[414] Andreini, Parlange, and Steenhuis, 1990; Ahuja, Barnes, and Rojas, 1993.
[415] Quisenberry et al., 1993.
[416] Helling and Gish, 1991.
[417] Goss et al., 1993.

encourage the activity of earthworms which may result in a greater continuity of macropores. Hence, contaminants may break through faster than predicted.[418]

A relatively large water content at the time of application might result in deeper movement of contaminants,[419] but the opposite effect has also been reported.[420] Understanding the mechanism of bypass flow through convection and diffusion from regions with small pores to those with large pores may help to explain such differences.

3.3.4.1 *Summary*

For contaminants in manure, preferential flow is important to their transport through the soil and hence into water resources.

3.3.5 Transport of contaminants from manure

Little detailed information is available on the transport of contaminants from manure other than N and P. Nitrogen, phosphorus, and organic compounds from manure can be removed by surface runoff, affecting surface water quality, and can be leached from the soil, contaminating groundwater. Runoff generally accounts for only a small portion of applied-N compared with the leached portion.[421] For example, after two growing seasons, less than 2% of fertilizer-N was lost to runoff whereas 30% had moved below 1 m in the soil.[422] The actual proportions of nutrients lost vary according to cropping practices and the type and timing of manure application.

Sharpley investigated N- and P-runoff on ten Oklahoma soils amended with poultry litter.[423] Increasing the time between litter application and rainfall from

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[418] E. Munyankusi, S .C. Gupta, J.F. Moncrief., and E.C. Berry, 1994, "Earthworm macropores and preferential transport in a long-term manure applied Typic Hapludalf," *Journal of Environmental Quality*, 23, p. 733.
[419] Quisenberry and Phillips, 1976.
[420] R.E. White, J.S. Dyson, Z. Gerstl, and B. Yaron, 1986, "Leaching of herbicides through undisturbed cores of a structured clay soil," *Soil Science Society of America Journal*, 50, p. 277.
[421] B. Burgoa, R.K. Hubbard, R.D. Wauchope, and J.G. Davis-Carter, 1993, "Simultaneous measurement of runoff and leaching losses of bromide and phosphate using tilted beds and simulated rainfall," *Communications in Soil Science and Plant Analysis*, 24, p. 2689.
[422] Blevins et al., 1996.
[423] A.N. Sharpley, 1997, "Rainfall frequency and nitrate and phosphorus runoff from soil amended with poultry litter," *Journal of Environmental Quality*, 26, p. 1127.

1 to 35 days reduced total-N in runoff from 7.54 to 2.34 mg/L, NH_4^+-N from 5.53 to 0.11 mg/L, dissolved-P from 0.74 to 0.45 mg/L, and bioavailable-P from 0.99 to 0.65 mg/L. When litter was applied 7 days prior to the first rain, runoff N- and P-concentrations decreased with each of 10 successive rains. However, NO_3^- concentrations were unaffected by rainfall frequency and timing.

3.3.5.1 *Nitrogen*

N in manure solids left on the soil surface, or associated with fine particles that are readily moved during soil erosion, can be lost through surface runoff to a watercourse. The factors that determine N-loss by erosion are:

- the amount of sediment moved,
- the N-content of the soil moved, and
- the N-content of the manure solids.

N dissolved in runoff water is also subject to loss to surface water. Although this portion is usually small,[424] it is very variable and depends on a number of factors, such as the degree of soil cover, source of N applied, application rate, and timing and duration of the application. Surface conditions are also important, and are affected by slope, soil characteristics, and land management. Finally, runoff is highly dependent on the intensity of rainfall after application. The largest losses occur if a soluble-N source is applied to a bare soil surface and a significant rainfall event occurs soon after application.[425] In many cases, most of the dissolved-N is transported into the soil with the initial infiltration that precedes runoff.[426]

Intensive rainfall shortly after fertilizer application generates the largest loss of NO_3^- in runoff.[427] However, in the lower southern coastal plain of the United States, most of the loss of NO_3^- in runoff was from sub-surface flow in the top 30 cm of soil rather than from surface flow. Over a 10-year period, 20% of the N in the applied fertilizer was lost via surface and subsurface flow.[428] This was

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[424] Blevins et al., 1996; Meisinger and Randall, 1991.

[425] D.R. Edwards and T.C. Daniel, 1993, "Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescue grass plots," *Journal of Environmental Quality*, 22, p. 361; Sharpley, 1997.

[426] Meisinger and Randall, 1991.

[427] R.K. Hubbard and R.G. Sheridan, 1983, "Water and nitrate losses from a small upland coastal plain watershed," *Journal of Environmental Quality*, 12, p. 291; Hubbard, Leonard, and Johnson, 1991; Lowrance, 1992.

[428] Hubbard and Sheridan, 1983.

comparable with the loss in runoff reported by Edwards and Daniel for conditions of high rainfall intensity.[429] Such results suggest that tile-drainage systems can greatly reduce groundwater contamination at the expense of surface water contamination. However, not all drainage water may be intercepted by pipe drains, even during major flow events, so groundwater contamination is still likely.

The major N species lost by leaching is NO_3^-. If economically optimum rates of N are applied to row crops such as corn, NO_3^--N losses by leaching from the root zone may be in excess of 10 mg/L, the maximum acceptable concentration in drinking water.[430] Only when plants were visibly deficient in N were the average NO_3^- concentrations (corrected for flow rate) in the leachate below 10 mg N/L.[431] A study on optimum nitrogen and irrigation inputs for corn found that by applying urea-based fertilizer at 95% of that required for maximum yield, nitrate leaching could be reduced by 30 to 40%; and by using a variable deficit trigger for scheduling irrigation, nitrate leaching could be reduced by 50 to 55%.[432] At equivalent N rates, turkey manure produced equal or better crop yields than urea applications and NO_3^- leaching was equal to or less than that with urea.[433] Dairy manure applied to a corn field resulted in similar or slightly smaller NO_3^- loading than agronomically equivalent rates of fertilizer-N.[434] In contrast, Nielsen and Jensen reported that NO_3^--N losses from the rooting zone in soils amended with liquid manure were greater than those from a similar soil to which the same amount of N had been applied as inorganic fertilizer.[435] Jemison and Fox found very little difference in NO_3^- concentrations or mass of NO_3^- leached between non-manured corn and corn manured at the economically optimum rate.[436] The different results for the amount of NO_3^- leached following manure applications highlights the importance of N-transformations, such as mineralization and denitrification, that influence the availability of nitrate in the soil.

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[429] Edwards and Daniel, 1993.

[430] J.M. Jemison and R.H. Fox, 1994, "Nitrate leaching from nitrogen B fertilized and manured corn measured with Zero-tension pan lysimeters," *Journal of Environmental Quality*, 23, p. 337; Toth and Fox, 1998.

[431] Jemison and Fox, 1994.

[432] B.T. Sexton, J.F. Moncrief, C.J. Rosen, S.C. Gupta, and H.H. Cheng, 1996, "Optimizing nitrogen and irrigation inputs for corn based on nitrate leaching and yield on a coarse-textured soil," *Journal of Environmental Quality*, 25, p. 982.

[433] Ibid.

[434] W.E. Jokela, 1992, "Nitrogen fertilizer and dairy manure effects on corn yield and soil nitrate," *Soil Science Society of America Journal*, 56, p. 148.

[435] N.E. Nielsen and H.E. Jensen, 1990, "Nitrate leaching from loamy soils as affected by crop rotation and nitrogen fertilizer application," *Fertilizer Research*, 26, p. 197.

[436] Jemison and Fox, 1994.

Loss of N is affected greatly by soil water content.[437] Nitrate leaching tends to be greatest when the soil is wet during the late fall, before the soil freezes, and again in the early spring. It may be minimized by applying manure during the late spring and early summer when crops can compete for NO_3^- with the smaller volume of water that moves downward through the unsaturated layers of the soil.[438]

Alfalfa crops, or including alfalfa in the crop rotation, considerably reduced the amount of NO_3^- leaving a farm in leachate.[439] This effect is attributed to a longer period of evapotranspiration resulting in less drainage, as well as greater uptake and immobilization of N by the perennial crop. In a dry year when plant growth and N-uptake are limited and percolation of soil water is negligible, mineralization continues to occur. Mineral-N accumulates in the soil profile and will be subject to leaching when precipitation exceeds evapotranspiration.

Large soil pores increase the movement of NO_3^- when it is mixed with infiltrating water. The greater the initial soil water content, the deeper the penetration within the macropores because less water moves laterally into the micropore system.[440] When the soil water content is close to field capacity, the micropore space is filled with water and application of more solution, such as liquid manure, tends to encourage flow in the macropore space.[441]

Few studies compare the potential for nitrate leaching of different manure types. Younie et al. found that nitrate leaching was higher where liquid cattle manure was the source of nitrogen than where solid beef manure was used.[442] Ritter et al. studied soil-nitrate profiles under 16 sites, some of which received fertilizer-N alone or in combination with either broiler manure or liquid swine manure.[443] Although direct comparison of manure types was not made on the same site, N-application rate was found to be the major determinant of N in the soil profile. It appears that manure from poultry, cattle, or pig operations has the potential to contaminate groundwater if it is applied at excessive rates.

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[437] G.W. Randall and T.K. Iragavarapu, 1995, "Impact of long-term tillage system for continuous corn on nitrate leaching to tile drainage," *Journal of Environmental Quality*, 24, p. 360.
[438] P.L. Adams, T.C. Daniel, D.R. Edwards, D.J. Nichols, D.H. Pote, and H.D. Scott, 1994, "Poultry litter and manure contributions to nitrate leaching through the vadose zone," *Soil Science Society of America Journal*, 58, p. 1206.
[439] Toth and Fox, 1998.
[440] Beven and Germann, 1982.
[441] Unc and Goss, 2000.
[442] M.F. Younie, D.L. Burton, R.G. Kachanoski, E.G. Beauchamp, and R.W. Gilham, 1996, *Impact of Livestock Manure and Fertilizer Application on Nitrate Contamination of Groundwater*, Final report for the Ontario Ministry of Environment and Energy, RAC No. 488G.

Liquid manure adversely affected tile-water quality when applied to the land following the current Ontario farming guidelines. Dean and Foran found that 75% of the manure-spreading events they investigated resulted in water quality impairment.[444] It appears difficult to determine an acceptable application rate of liquid manure due to the numerous factors which affect the contamination of watercourses.[445] Pre-tillage is the management technique best able to minimize the potential for contamination of tile drains from liquid manure.[446]

3.3.5.2 *Phosphorus*

More P is likely to be lost in surface runoff than by leaching.[447] Where liquid or solid manure was not incorporated after application, the loss of phosphorus in surface runoff was greater from ploughed soil than from land that was under no-till. Loss from no-till land was similar to that from land where the manure had been incorporated after application.[448]

As P is a reactive ion, soil enrichment generally decreases sharply with depth. Application of cattle feedlot waste resulted in an increased proportion of available-P in the first 30 cm, but with little increase below 50 cm.[449] Decreasing enrichment or only slight enrichment with depth does not necessarily indicate no leaching because the residence time of some drainage water in the subsoil may have been too short, perhaps because of preferential flow, to allow adsorption of P onto soil particles.[450] Furthermore, some subsoils (e.g., sandy soils) may have limited capacity to retain P.

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[443] W.F. Ritter, A.E.M. Chirnside, and R.W. Scarborough, 1990, "Soil nitrate profiles under irrigation on coastal plain soils," *Journal of Irrigation and Drainage Engineering*, 116, p. 738.
[444] D.M. Dean and M.E. Foran, 1992, "The effect of farm liquid waste application on tile drainage," *Journal of Soil and Water Conservation*, 47, p. 368.
[445] Foran, Dean, and Taylor, 1993.
[446] Fleming and Bradshaw, 1992b.
[447] A.N. Sharpley and P.J.A. Withers, 1994, "The environmentally-sound management of agricultural phosphorus," *Fertilizer Research*, 39, p. 133; K.A. Smith, A.G. Chalmers, B.J. Chambers, and P. Christie, 1998, "Organic manure phosphorus accumulation, mobility and management," *Soil Use and Management*, 14, p. 1549.
[448] King et al., 1994.
[449] L.B. Campbell and G.J. Racz, 1975, "Organic and inorganic P content, movement and mineralization of P in soil beneath a feedlot," *Canadian Journal of Soil Science*, 55, p. 457.
[450] A.E. Johnston and P.R. Poulton, 1997, "The downward movement and retention of phosphorus in agricultural soils," *Phosphorus Loss from Soil to Water*, H. Tunney, O.T. Carton, P.C. Brookes, and A.E. Johnston (eds.), (Wallingford, UK: CAB International), p. 422.

Leaching of P from manure may occur in both inorganic and organic forms.[451] Complexation of P with mobile organic compounds may favour the deep transport of P in organic forms even through layers with a great P-adsorption capacity, such as carbonate soil layers. Experimental results showed that P from mineral fertilizer did not move under the carbonate layer (0.9 m) of soil even after 40 years of mineral-P fertilization, while organic-P from manure moved up to 1.8 m.[452] The P-movement in this soil was found to be unaffected by the P-adsorption of the soil.

Phosphorus association with low-molecular-weight organic acids favoured increased mobility through both decreased adsorption and increased dissolution of P-compounds leading to greater bioavailability[453] and to an enhanced risk of leaching. Increasing labile, weakly bound-P results in a greater vulnerability of manure-treated soils to lose phosphorus by leaching.[454] This results in deeper penetration of P-compounds after manure application.[455]

Leaching of P from soil in water-soluble and particulate forms is enhanced by the presence of tile drainage.[456] If a critical concentration of soluble-P in the ploughed layer was exceeded, an enhanced contribution of P-losses resulted through tile drains in clay loam soils.[457] P-losses in tile-drain effluent were increased where manure was applied, compared with unfertilized control plots.[458] Subsurface transport of P may occur as water-soluble-P and as particulate-P in both undrained and tile-drained plots.[459]

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[451] Campbell and Racz, 1975; B. Eghball, G.D. Binford, and D.D. Baltensperger, 1996, "Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application," *Journal of Environmental Quality*, 25, p. 1339.
[452] Eghball, Binford, and Baltensberger, 1996.
[453] N.S. Bolan, R. Naidu, S. Mahimairaja, and S. Baskaran, 1994, "Influence of low-molecular-weight organic acids on the solubilization of phosphates," *Biology and Fertility of Soils*, 18, p. 311.
[454] R.E. Stephenson and H.D. Chapman, 1931, "Phosphate penetration in field soils," *Journal of the American Society of Agronomy*, 23, p. 759.; J.S. Robinson, A.N. Sharpley, and S.J. Smith, 1995, "The effect of animal manure applications on the forms of soil phosphorus," *Animal Waste and Land-water Interface*, K. Steele (ed.), (Boca Raton, FL: CRC Press), p. 43; Johnston and Poulton, 1997.
[455] Campbell and Racz, 1975.
[456] A.F. Harrison, 1987, *Soil Organic Phosphorus: A Review of World Literature* (Wallingford: CAB International).
[457] G. Heckrath, P.C. Brookes, P.R. Poulton, and K.W.T. Goulding, 1997, "Phosphorus losses in drainage water from an arable silty clay loam," *Phosphorus Loss from Soil to Water*, H. Tunney, O.T. Carton, P.C. Brookes, and A.E. Johnston (eds.), (Wallingford, UK CAB International), p. 367.
[458] G.W. Hergert, D.R. Bouldin, S.D. Klausner, and P.J. Zwerman, 1981, "Phosphorus concentration-water flow interactions in tile effluent from manured land," *Journal of Environmental Quality*, 10, p. 338.
[459] R.M. Dils and A.L. Heathwaite, 1997, "Phosphorus fractionation in grassland hill-slope hydrological pathways," *Phosphorus Loss from Soil to Water*, H. Tunney, O.T. Carton, P.C. Brookes, and A.E. Johnston (eds.), (Wallingford, UK: CAB International), p. 349.