

Pesticides in the Environment: Real or Imagined

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Abstract

Pesticide use has become an integral component of most crop and animal production systems in Canada. Pesticides are known to move from treated agricultural areas into the broader environment through atmospheric transport and transport in water. They enter the atmosphere through application drift, post-application vapour losses and wind-eroded soil and can subsequently contaminate surface waters via wet (precipitation) and dry (particulate) atmospheric deposition. Surface waters can also become contaminated with pesticides through rainfall, snow melt and irrigation runoff. Ground waters may become contaminated by leaching. As a consequence of environmental transport, pesticides have been detected in air and rainfall, surface waters (farm dugouts and ponds, wetlands, rivers and streams) and ground waters (private and municipal wells) across Canada.

Introduction

In Canada, agricultural production occurs in all ten provinces but the extent to which the landscape has been permanently modified by agricultural activities varies from < 1 of the Pacific Maritime ecozone to 90% of the Prairie ecozone. Consequently, pesticide use, which has become an integral component of most crop and animal production systems in Canada, also varies widely across the country (Table 1).

Table 1. Percent Pesticide Sales by Province in Canada (1998).

Province	Sales ^a	Percent sales
British Columbia	\$89 M	7%
Alberta	\$216 M	17%
Saskatchewan	\$457 M	36%
Manitoba	\$229 M	18%
Ontario	\$203 M	16%
Quebec	\$51 M	4%
Atlantic region	\$25 M	2%

^a CropLife Canada 1999

Pesticides are known to move from treated agricultural and forested areas into the broader environment. It is generally accepted that the broad diffusion of pesticides into the environment is associated with atmospheric transport and transport in water. Pesticide presence in the atmosphere occurs by three main routes of entry: these include application drift, post-application vapour losses and wind erosion of treated soil (Figure 1). Once pesticides have entered the atmosphere, they, or their photodegradation products, may be transported long distances before

the removal processes of atmospheric wet (precipitation) and dry (particulate) deposition return them to the earth's surface. These removal processes contribute directly to pesticide loadings in surface waters and may indirectly contribute to loadings in ground waters.

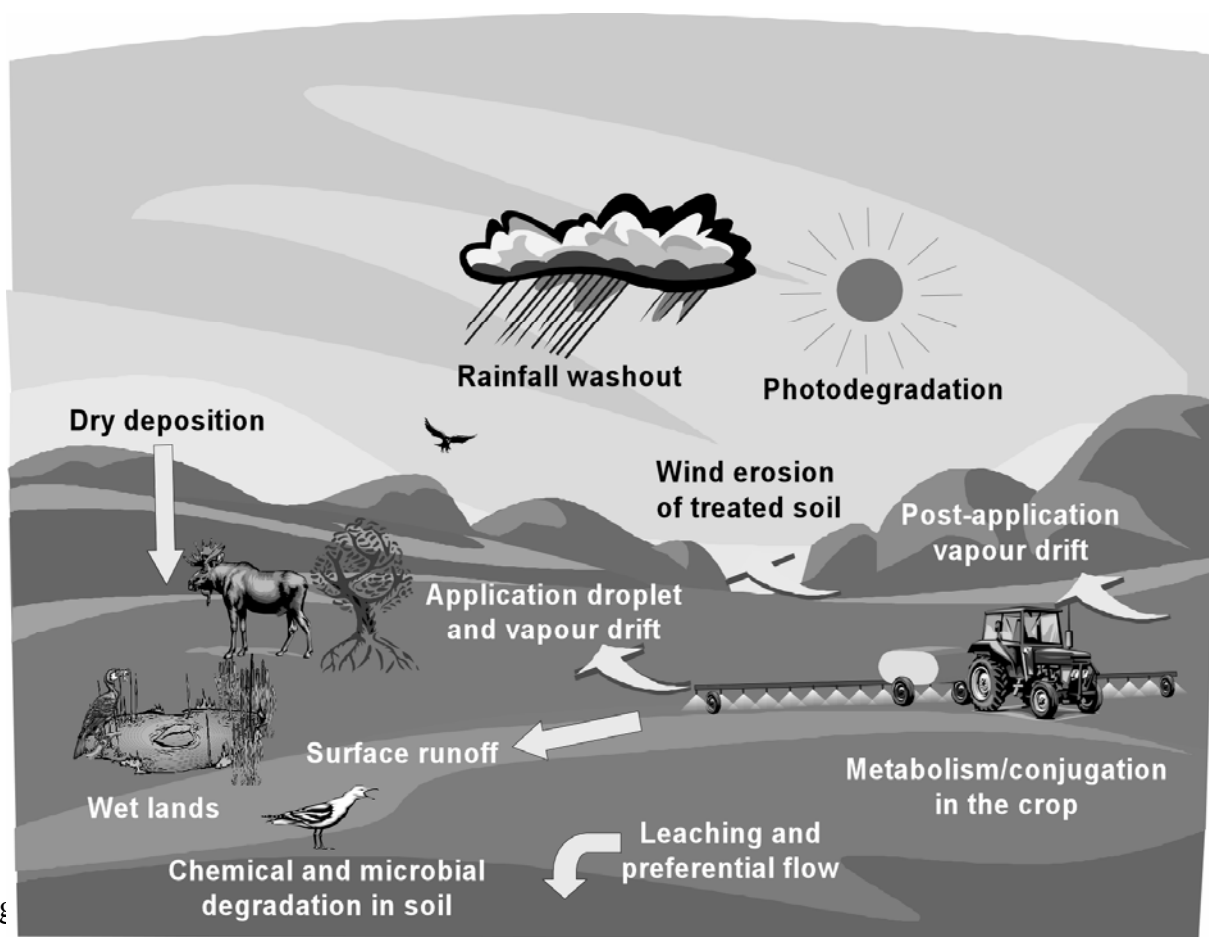


Fig and mechanisms of pesticide transformation in air, soil and plants

Transport in surface (irrigation, rainfall or snow melt) runoff also contributes to pesticide contamination of surface (receiving) waters. When pesticide-contaminated runoff enters a water body (lake, wetland, constructed reservoir), pesticides entering the water body are generally those applied within its watershed and further transport is generally restricted to dispersion within the water body. When surface runoff enters flowing water (river or stream), then not only is it possible for pesticides to be transported long distances but a diversity of pesticides may be present due to multiple watersheds which may occur along the reach of a river or stream. Transport by leaching may lead to contamination of ground water with pesticides. Leaching may consist of matrix flow and/or preferential flow. Preferential flow results in relatively rapid movement of water and dissolved pesticides to depth in soil and occurs via preferential pathways

such as cracks or fissures in the soil or continuous macropores consisting of insect burrows or cavities left by decayed plant roots.

There is increasing awareness by the Canadian public about this diffusion of pesticides into the environment and its potential to impact human health and environmental quality. Public interest in human health issues with respect to chemical use is high and Canadians remain concerned with air quality and the safety of their drinking water and food supply. Effects of chemicals on wildlife habitat and biodiversity are also important to Canadians as evidenced by the popularity of wildlife- and fish-related activities, and strong commitment to the protection and conservation of abundant and diverse wildlife.

There is increasing awareness that atmospheric transport and deposition of pesticides plays a major role in their dispersion into the broader environment. Consequently, in this presentation, the routes of entry of pesticides into the atmosphere will be discussed in detail along with entry into surface and ground waters. Finally, the impact of pesticides on air, surface water and ground water quality in Canada will be discussed.

Entry of Pesticides into the Atmosphere

Application Drift

Liquid sprays are applied through nozzles which provide metering, atomization, and uniform distribution of the pesticide mixture. The majority of atomizers use hydraulic pressure as the energy source for breaking the liquid into droplets. Hydraulic atomizers such as flat fan nozzles produce a heterogeneous spray, i.e., one that contains a spectrum of droplet sizes. A typical flat fan nozzle, for example, produces droplet sizes between 5 and 700 μm in diameter.

The proportion of the total spray volume contained in droplet sizes below 150 μm can be used as an indicator of drift potential, because it is these small droplets that are most prone to movement under windy conditions. For conventional flat fan nozzles, the drift-prone size fraction typically varies between 10 and 30% of the total volume (depending on nozzle parameters and measurement methodology), whereas for low-drift nozzles, the value can be as low as 1%, but generally ranges between 1 and 5%. Low-drift adjuvants have also been shown to reduce the fine drop component of liquid sprays.

The amount of spray drift leaving a treated swath depends primarily on the droplet size spectrum of the spray, the height of droplet release, and weather conditions such as wind speed and atmospheric turbulence. Under typical daytime conditions with winds between 10 and 25 km h^{-1} , it has been shown that about 95% ($\pm 4\%$) of fine to medium sprays deposited on the treated swath whereas the remaining 5% ($\pm 4\%$) moved off-swath in the direction of the wind.

Post-Application Vapour Losses

In crop production, which accounts for the majority of agricultural use of pesticides in Canada, there are two broad types of pesticide applications. Preemergence applications, applied to the soil surface prior to the emergence of the crop, may be left undisturbed on the soil surface or incorporated by some form of soil disturbance into the upper layer of soil. Postemergence applications are applied directly to the crop/weed canopy, a portion of which will penetrate the

crop/weed canopy and deposit on the soil surface.

The magnitude of post-application vapour losses from soil and plant surfaces is dependent upon several factors. Losses of pesticides from plant surfaces depend primarily on the vapour pressure of the pesticide, as well as the rate of uptake by the plant, the rate of sunlight photodegradation on plant surfaces, and atmospheric turbulence to move vapours away from plant surfaces. Vapour losses within a week of postemergence application to wheat were 21% for 2,4-D *iso*-octyl ester, 16 and 7% for bromoxynil *n*-butyrate plus octanoate (1:1), respectively, and < 1% for diclofop-methyl.

Losses from soil surfaces are determined by the physical-chemical properties of the pesticide (eg., vapour pressure), the degree of incorporation or penetration of the pesticide into the soil, the extent of binding of the pesticide to soil components, the half-life of the pesticide in soil (eg., its susceptibility to microbial degradation), tillage system and environmental conditions, such as soil moisture and atmospheric turbulence above the soil surface, during and following application. For example, much greater vapour loss occurs when a pesticide is applied to moist soil with no incorporation compared to the same treatment on dry soil or when the pesticide is incorporated shortly after application. Under Saskatchewan conditions, vapour losses of preemergence incorporated applications of triallate and trifluralin were 18 and 24%, respectively.

Wind-Erosion of Pesticide-Treated Soil

Because of their use in many crop and animal production systems, pesticides are frequently present on the surface of agricultural soils. Pesticides on the soil surface may be susceptible to transport through wind erosion of soil in which three processes are considered operative. Large soil particles can roll on the soil surface under the influence of wind and this movement is called surface creep. Smaller particles can become suspended in the air for short periods of time as they move laterally. This process is known as saltation. Even smaller particles can remain suspended in the air as they move laterally, and this process is termed suspension. Since all three processes may involve soil particles with adsorbed pesticide, significant amounts of pesticide may be transported from the soil surface with the wind-eroded sediment.

In a southern Alberta study, overall losses for three winter wind erosion events for two soil-incorporated herbicides, trifluralin and triallate, were approximately 1.5% of the amounts applied. Simultaneous losses of four postemergence herbicides (2,4-D, mecoprop, bromoxynil, diclofop) applied to the soil surface averaged 4.5%. This and other studies demonstrate the potential for environmental transport of pesticides on wind-eroded sediment and its associated implications for off-site air and surface water quality.

Entry of Pesticides into Surface Waters

Atmospheric Deposition

Once pesticides enter the atmosphere either by application drift, post-application vapour losses or wind erosion of soil, they are subject to transport over distances which can range to thousands of kilometres. At any point during transport, they are also subject to the removal processes of wet (precipitation) and dry (particulate) deposition, both of which contaminate surface waters. In wet deposition, pesticides may be trapped in snow and hail or dissolved in rain. In dry deposition, pesticides sorbed to particles of wind-eroded soil or consisting of desiccated

application drift droplets or present in aerosols settle to the earth's surface by gravitational influence. Dry deposition also includes the sorption of pesticides present as vapours in the atmosphere onto surfaces near the earth's surface. In either process, the pesticides deposited may have originated from the region of application or they may have been transported long distances prior to their removal.

Surface Runoff

Surface waters receive a portion of their water from snow melt or rainfall runoff. Pesticides susceptible to surface runoff are those within the runoff-soil interaction zone or the top 0.5 to 1 cm of soil. Several factors may affect the amount of pesticide present within this zone. These include the type of pesticide application (soil surface-applied, soil-incorporated, or postemergence), soil type, the physical-chemical properties of the pesticide (vapour pressure, water solubility, soil sorption characteristics), the environmental stability or field half-life of the pesticide (resistance to hydrolysis, photodegradation and microbial degradation), the formulation type of the pesticide and atmospheric deposition of pesticides. Other factors affecting the amount of pesticides transported in surface runoff include the slope of the treated area and the interval between pesticide application and the occurrence of the runoff event. Generally, the greater the slope and the shorter the interval between application and runoff, the greater are the contaminant losses in surface runoff.

Losses of pesticides in rainfall runoff from agricultural land are generally 0.5% or less of the amounts applied, whereas those in flood-irrigation runoff are generally less than 2%. For example, in a Saskatchewan study, losses of diclofop and bromoxynil during the flood irrigation of wheat were approximately 1% of the amount of each herbicide applied (Table 2).

Table 2. Herbicide transport in runoff from flood-irrigation of wheat.

Herbicide	Loss in drainage water (time between herbicide application and flood irrigation)		
	----- % -----		
Bromoxynil	0.83%	0.12	0.02%
	(7 hours)	(13 days)	(26 days)
Diclofop	0.79%	0.12%	0.03%
	(7 hours)	(13 days)	(26 days)

Entry into Ground Water

Leaching

Leaching of water and dissolved pesticides to depth in soil occurs by matrix flow and/or preferential flow. Matrix flow is the slower transport process in which the simultaneous movement of pesticides with water is determined largely by the physical-chemical properties of the pesticides. Such movement of a pesticide is dependent on its water solubility, vapour pressure, Henry's Law constant (which defines its partitioning between air and water), and soil sorption coefficient.

Preferential flow consists of more rapid movement of water to depth via preferential pathways such as insect burrows, soil fractures and cavities left by decayed plant roots. In preferential flow, the rate of simultaneous pesticide transport is largely independent of the physical-chemical properties of the pesticide. Preferential flow of pesticides is considered to occur when pesticides with differing mobility characteristics are leached to the same depth or appear simultaneously in tile-drain effluent. However, unlike the rate of pesticide transport, the amount of pesticide transported does depend on the mobility characteristics of the pesticide.

When there is no heavy rainfall shortly after pesticide application, the mass of pesticide annually leached below the root zone generally is in the range of < 0.1 to 1% of the amount applied. Similar amounts being leached under sprinkler irrigation have been reported in a Saskatchewan study. Although some researchers reported that greater leaching of pesticides occurred with zero versus conventional tillage, others have concluded that tillage practice or soil surface management may influence pesticide leaching in some cases but not in others and that the factors causing these differences are not well understood.

Impacts of Pesticide Use on Air and Water Quality in Canada

Agricultural pesticide use has become an integral component of most crop and animal production systems in Canada. As a consequence, greater than 45 million kilograms of pesticide active ingredient are used annually in Canada with annual sales exceeding one billion Canadian dollars. Herbicides account for about 80% of all pesticides sold (Table 3) with approximately 70% of pesticide sales occurring within the three prairie provinces of Alberta, Saskatchewan and Manitoba (Table 1).

Table 3. Pesticide Sales in Canada (2001).

Pesticide	Sales ^a	Percent sales
Herbicides	\$1.016 B	80
Insecticides	\$0.064 B	5
Fungicides	\$0.114 B	9
Other	\$0.076 B	6
Total	\$1.270 B	100

^aCropLife Canada 2002

Impacts on Air Quality

Once pesticides have entered the air, they are subject to atmospheric transport. The extent to which they move in the atmosphere before depositing to the earth's surface via atmospheric deposition can vary greatly. Distances moved can be local (less than one to tens of kilometres), regional (hundreds of kilometres) or long-range (thousands of kilometres) in nature.

Ambient Air Concentrations: Inputs of pesticides into the atmosphere have resulted in detectable ambient air concentrations of pesticides in Canada. As early as the late 1960s, the herbicide 2,4-D, as its *iso*-propyl, mixed butyl and *iso*-octyl esters, was detected in ambient air

samples collected at several sites in Saskatchewan when concentrations as high as 23,140 ng m⁻³ were measured. More recently, triallate, trifluralin, 2,4-D, MCPA, dichlorprop, dicamba, bromoxynil, diclofop, chlorpyrifos, chlorthal-dimethyl and pentachlorophenol concentrations have been measured in air samples of studies carried out in Saskatchewan and Manitoba. In 1988/89, trifluralin and endosulfan concentrations were measured in an Ontario study. The majority of the pesticides in these studies were present in the atmosphere mainly in the vapour phase with the remainder associated with atmospheric particles. Ambient air pesticide concentrations in the more recent studies have generally been less than 100 ng m⁻³.

Concentrations in Wet Deposition: In wet deposition, pesticides may be trapped in snow and hail or dissolved in rain. In the prairie region of Canada, bulk (dry plus wet) atmospheric deposition of pesticides has been measured in Alberta, Saskatchewan and Manitoba. In each province, herbicides detected in bulk deposition samples reflected regional use patterns and highest deposition rates were measured during the regional spraying period. In the Alberta study, 16 pesticides were detected. Herbicide concentrations were highest (Table 4) in samples which included rainfalls of 0.1 to 0.2 mm, indicating that washout of ambient air concentrations occurred early in rainfall events. In terms of spatial distribution, concentrations were lowest in samples from remote areas, intermediate in urban centres, and highest in rural farm areas. Generally, more than one pesticide was detected in the bulk samples. In other studies, endosulfan has been detected in rainfall samples from Ontario, Prince Edward Island and Nova Scotia. Trifluralin and endosulfan have been detected in snow samples from the Arctic, the Rocky Mountains of British Columbia and Alberta, and Atlantic Canada.

Table 4. Concentration ranges of the five herbicides detected in greatest amounts in bulk atmospheric deposition samples collected in Alberta (1999 - 2000).

Herbicide	Concentration Range
	----- µg L ⁻¹ -----
2,4-D	< 0.025 to 53
MCPA	< 0.025 to 26
Bromoxynil	< 0.025 to 26
Dicamba	< 0.025 to 9.1
Mecoprop	< 0.025 to 2.5

Concentrations associated with Particles: In dry deposition, pesticides may be sorbed to particles of wind-eroded soil, consist of desiccated application drift droplets or be present in aerosols. These particles and associated pesticides settle to the earth's surface by gravitational influence. Dry deposition also includes the sorption of pesticides present as vapours in the atmosphere onto surfaces near the earth's surface. In a recent study in which a new sampling technology that permits separate collection of wet and dry atmospheric deposition was employed, dry deposition of 2,4-D and dicamba at two sites in Saskatchewan was reported. During the May/August period, average dry deposition rates for 2,4-D ranged from 42 to 262 ng m⁻² d⁻¹, whereas those for dicamba ranged from deposition of trace amounts to 67 ng m⁻² d⁻¹.

Impacts on Surface Water Quality

Inputs due to the atmospheric processes of wet and dry deposition and downwind deposition of application drift, together with surface runoff inputs, have resulted in detectable concentrations of pesticides in a variety of surface waters across Canada.

Wetlands: In a recent study in Saskatchewan, in which wetlands situated in wildlife habitat and on farms of high (zero tillage), moderate (conventional tillage) and no (organic farming) pesticide inputs were monitored for herbicide content, the frequency of detection and concentrations of individual herbicides were similar regardless of land-use type. The authors suggested that atmospheric processes could account for both the concentrations and relatively uniform distribution of herbicides in the wetlands on all landscape types even though the intensity of pesticide use varied within their immediate vicinities. In another Saskatchewan study, both the mean number of herbicide detections in wetlands and the number of wetlands with herbicide concentrations exceeding water quality guidelines for aquatic life increased with increasing rainfall. Herbicide concentrations in the wetlands were generally less than $1 \mu\text{g L}^{-1}$.

Farm Dugouts and Ponds: Since surface runoff is the principal source of water for the majority of farm dugouts or ponds, the presence of pesticides in their waters would not be unexpected. However, in spite of their frequency of occurrence across the Canadian agricultural landscape and the multifunctional purpose for which these water bodies are used, few studies have reported on pesticide content in these water bodies.

In Alberta in 1994, 112 farm dugouts were monitored for herbicide content as part of the Farmstead Water Quality Survey. Based on a single water sampling during August, herbicide residues were detected in 47% of on-farm surface (dugouts and other sources) water supplies. Herbicides most commonly detected included 2,4-D, MCPA, bromoxynil and dicamba.

In a 2-year (1987/88) study in Saskatchewan, 21 farm dugouts, situated within four major soil zones, were sampled following snow melt, after spring herbicide application, and in the fall prior to freeze up. Herbicides were detected in all dugouts with frequent detections of more than one herbicide in a dugout. Maximum concentrations tended to be seasonal and, in general, tended to be less than $5 \mu\text{g L}^{-1}$. The decreasing frequency of detection in these dugouts was 2,4-D > diclofop > bromoxynil > MCPA > triallate > dicamba > trifluralin. In another study, chlorpyrifos concentrations exceeded $20 \mu\text{g L}^{-1}$ following aerial application of the insecticide in the vicinity of the dugout.

In Ontario, 212 farm ponds were monitored for pesticide content in 1986 and 1989. Pesticides were detected in 63% of the ponds and, of the 29 (22 herbicides, 6 insecticides and 1 fungicide) pesticides detected, the most frequently detected was atrazine followed by 2,4-D, simazine, PCP, dichlorprop and endosulfan. Highest concentrations were associated with accidental spills. Mean concentrations attributed to inputs from application drift and surface runoff were lowest and generally less than $10 \mu\text{g L}^{-1}$.

The pesticides detected in prairie dugouts and Ontario farm ponds generally reflected both use patterns within the vicinities of the water bodies and the environmental stability (field half-lives) of the pesticides. Entry of these pesticides into the dugouts in the abovementioned studies may

have been on-going for several decades via surface runoff and/or atmospheric deposition because of long-term use. For example, of the herbicides detected in the Saskatchewan dugouts, 2,4-D and MCPA have been in use in the prairie region for more than 50 years, dicamba, mecoprop, triallate and trifluralin for about 40 years, bromoxynil for approximately 30 years, diclofop for 20 years, and clopyralid and ethalfluralin for about 10 years. Such long-term use may, in part, account for the presence of pesticides in these water bodies. Also, if pesticides are present in the bottom sediments of these water bodies, then under appropriate environmental conditions, the sediments may act as a source of the pesticides to the water column. Thus, the median concentrations of pesticides detected in these water bodies may be an indicator of the general level of contamination of farm dugouts and ponds due to agricultural use within their vicinities.

Lakes. Only two studies have investigated pesticide concentrations in Canadian lakes. In 1989, herbicide (2,4-D, MCPA, atrazine, dicamba, trifluralin, triallate and picloram) concentrations were monitored in 10 permanent and 9 semi-permanent lakes in southern Saskatchewan. Herbicides detected in lake water included 2,4-D, MCPA, atrazine, and dicamba, whereas triallate, atrazine, bromoxynil, MCPA and 2,4-D were detected in the sediments. Detection frequencies tended to decrease as the lakes became more saline. In 1995/1996, 25 Alberta lakes were monitored for 13 pesticides. Pesticide detections in the lake waters reflected agricultural pesticide use with 2,4-D and MCPA being most frequently detected, followed by dicamba, imazamethabenz, and triallate. Those less frequently detected included bromoxynil, trifluralin, picloram and diclofop. Five of the pesticides were also detected in lake sediments.

Rivers and Streams: As early as the mid-1970s, rivers in Ontario and Quebec were contaminated with agricultural pesticides. Atrazine and its metabolite desethylatrazine were detected in five rivers in the Yamaska river basin of Quebec in 1974/1975. The highest levels of atrazine coincided with the regional spraying period and losses of atrazine to the rivers ranged from 0.1 to 2.9% of amounts estimated to have been applied in each watershed. In 1986/1987, atrazine and metolachlor and 8 other pesticides were detected in the Yamaska River.

In 1975/1977, 18 pesticides (11 herbicides and 7 insecticides) and 3 metabolites were detected in streams draining 11 agricultural watersheds in southern Ontario. Pesticide detections in the streams generally coincided with the regional spraying season and reflected pesticides used within the watersheds. In a later 5-year study, the Grand, Saugeen and Thames rivers in Ontario were monitored from 1981 to 1985 for 48 pesticides. The order of loading in the rivers by pesticide class was triazine herbicides > chloroacetanilide herbicides > chlorophenoxy plus chlorobenzoic acid herbicides > organochlorine insecticides. No fungicides were detected in the rivers and pesticide concentrations were generally less than $1 \mu\text{g L}^{-1}$. The Holland River in southern Ontario was monitored from 1990 to 1992 and, in addition to atrazine and metolachlor, several organophosphorus pesticides (terbufos, malathion, guthion, chlorpyrifos, ethion, dimethoate, phorate and disulfoton in concentrations $< 2.2 \mu\text{g L}^{-1}$) were detected in the river water. Chlorpyrifos, ethion and fonofos were also detected in the sediments. In 1991 and 1992, loadings of atrazine, its metabolite desethylatrazine and metolachlor in the Payne river were determined. In 1990 and 1991, atrazine and metolachlor concentrations were monitored in the Nissouri Creek agricultural watershed in southern Ontario which represented 0.015 and 0.01%, respectively, of amounts applied in the watershed.

In the late 1970s, 2,4-D, 2,4,5-T and dichlorprop were the most frequently detected pesticides in several prairie rivers (South Saskatchewan River, Red Deer River, North Saskatchewan River, Missouri River, Qu'Appelle River, Wascana Creek, Souris River, Red River and Assiniboine River). Pesticides detected from two sites on the Red River (1970 to 1990) included atrazine, 2,4-D, 2,4-DB, dicamba, dichlorprop, MCPA, picloram, 2,4,5-T, triallate and trifluralin. In 1984, concentrations of triallate, trifluralin, 2,4-D, MCPA, diclofop, dicamba and bromoxynil were detected in the Ochre and Turtle Rivers in northern Manitoba mainly during the spring spraying period and herbicide discharges in the two rivers were less than 0.1% of amounts estimated to have been applied in the respective watersheds. In 1993 to 1995, 16 pesticides were detected in the Red River and 7 of its tributaries in southern Manitoba during the period of spring snow melt runoff but were present at maximum concentrations during the regional spraying period. Pesticides detected most frequently in the tributaries were those used most extensively in the respective watersheds. Alachlor, which is not registered for use in Canada, was detected reflecting United States use of this herbicide. Atrazine, which was widely used in neighbouring U.S. states, was also detected in the Red River even though it was used only to a minor extent in Manitoba. In addition, urban use of chlorpyrifos, MCPA and 2,4-D in the city of Winnipeg contributed to pesticide loadings in the Red River.

In more recent studies (1993 to 1996), dichlorprop, 2,4-D, MCPA, bromoxynil, chlorpyrifos and chlorthal were detected in South Tobacco Creek which drains a small agricultural watershed in southern Manitoba. Highest concentrations were detected in the creek water during the spring application period and coincided with elevated concentrations of these herbicides in air and precipitation suggesting that the most likely source of these pesticides was atmospheric processes. Less than 0.01% of the amounts of these herbicides applied within the watershed were discharged in the water flow of the creek. Concentrations of chlorthal, which was not applied to the watershed in any year, must have been derived from long-range atmospheric transport and deposition processes.

In 1995/1996, 27 streams in Alberta were monitored for 13 pesticides. The streams drained land which ranged from high to low intensity agriculture. Ten of the streams were intermittent and flowed mainly during spring snow melt. Nine pesticides were detected in the stream waters with 2,4-D, MCPA and triallate the most frequently detected in high intensity agriculture areas. Detection frequency reflected pesticide use patterns, with most detections being made in April, the time of year when most surface runoff occurs.

Impacts on Ground Water Quality

During the 1980s to the mid-1990s, it became evident that some ground water supplies in Canada were contaminated with agricultural pesticides. In British Columbia, several pesticides (dimethoate, diazinon, atrazine, simazine, carbofuran, dinoseb, endosulfan and alachlor) were detected in ground water collected from the Abbotsford aquifer during the period 1984 to 1990. In the Fraser Valley (1992/1993), pesticides (oxamyl, bromacil and 1,2-dichloropropane) were detected in 2% of the wells (75 private and 192 community wells).

In 1995 and 1996, 824 Alberta farm wells, of which 84% (692) were used for drinking purposes and 54% (445) were considered to be deep wells (>30 m in depth), were monitored for herbicide

content. Herbicides (dicamba, MCPA, bromoxynil, 2,4-D, fenoxaprop, triallate and trifluralin) were detected in only 3% (27; 9 deep and 18 shallow) of the wells.

In Saskatchewan in 1987 and 1988, 2,4-D, diclofop, dicamba, MCPA, triallate and bromoxynil were detected in shallow ground water under irrigated fields in the Outlook Irrigation District. Natural springs in Saskatchewan, which drained shallow aquifers in which no wells were present, were monitored from 1991 to 1994. Herbicides, at concentrations $< 1 \mu\text{g L}^{-1}$, were detected in 23% of the samples with atrazine, picloram and 2,4-D most frequently detected. In 1996, 184 farm wells less than 15 m deep and situated into unconfined shallow aquifers that were highly vulnerable to contamination from surface sources, were analysed for pesticide content. One or more pesticides was detected in 26% (48) of the wells with the following frequency of detection: 2,4-D > MCPA > bromoxynil > dicamba > triallate > pentachlorophenol > picloram > atrazine > diclofop). The higher frequency of herbicide detection, relative to that in Alberta wells, probably reflects the much shallower depths of the wells and, consequently, greater susceptibility to contamination. In 1982/1982, chlorothalonil and carbofuran were detected in ground water in southern Manitoba.

In Ontario, 38% of 359 farm wells were contaminated with pesticides in the early 1980s. In a later ground water monitoring study (1985 to 1988), in which wells were selected to ensure that they were properly constructed and maintained, were not susceptible to surface runoff, and had no history of pesticide spills at or near the wellhead, 37% of 315 wells contained detectable concentrations of pesticides (atrazine, metolachlor, simazine, metribuzin, cyanazine, prometryn and alachlor). More recently, of more than 1,200 domestic farm wells monitored in Ontario during the summer of 1992, the majority (900) of which were located in areas of intense agriculture, 12% had detectable concentrations of the same pesticides

Surveys of farm wells on Prince Edward Island in 1983/1984 indicated that the insecticide aldicarb was present in 18% of high risk wells near potato fields. In studies from 1985 to 1988, aldicarb and its sulfoxide and sulfone degradation products were detected in a shallow sandstone aquifer more than two years after the last application of the pesticide. The pesticide has also been detected in ground water in New Brunswick.

In Nova Scotia, 41% of 102 farm wells, also situated in an area of intensive agriculture, had detectable concentrations of pesticides and 19% contained more than one pesticide. The frequency of detection, in decreasing order, was atrazine, simazine, metribuzin, alachlor, metolachlor, captan, chlorothalonil, dimethoate and permethrin.