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ASSESSING THE RISK OF GROUNDWATER NITRATE CONTAMINATION IN THE REGION OF WATERLOO, ONTARIO

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Abstract

In many areas of Ontario concentrations of nitrate in groundwater at levels above the Ontario drinking water limit of 10 mgL^{-1} constitute a serious threat to municipal drinking water supplies. In the Region of Waterloo permeable soils and high nitrogen application rates on farmland combine to produce high risk zones in a significant portion of the rural landscape. This study assesses the potential risk of agricultural land use on nitrate contamination in four well fields located west of the city of Waterloo. Secondary data from government documents and consultants' reports were used to develop GIS layers for soil drainage and nitrogen application rates by land use system. These layers were combined to produce a measure of risk of nitrate groundwater contamination associated with the combined effect of both factors. Results indicate that approximately 45% of the study area is at high risk. Two well fields, one of which was closed because nitrate levels exceeded the Ontario drinking water limit, have nearly 60% of their recharge areas in the high risk category. If this situation is to be improved, programs directed towards changing current nutrient management practices must be instituted.

Résumé

Dans bien des régions de l'Ontario, la concentration de nitrate dans les eaux souterraines dépasse la limite admise par la province pour l'eau potable (10 mg/l) et représente une sérieuse menace pour l'approvisionnement en eau potable des municipalités. Dans la région de Waterloo, la perméabilité du sol et les taux élevés d'application de nitrate sur les terres agricoles se combinent pour faire des secteurs environnants des zones à risque élevé. L'auteur de la présente étude évalue le risque que peut représenter l'exploitation agricole des terres sur la contamination au nitrate de quatre champs de captage situés à l'ouest de Waterloo. Il s'est servi de données secondaires de source gouvernementale et de rapports émis par des consultants pour cerner les couches SIG de drainage et les taux d'application d'azote selon le système d'utilisation des terres. Ces couches se combinent pour produire une mesure du risque de contamination au nitrate des eaux souterraines, sous l'effet des deux facteurs. Les résultats indiquent qu'environ 45 p. 100 des terres étudiées présentent un risque élevé. Deux champs de captage, dont un qu'il a fallu fermer parce que son niveau de nitrate dépassait la limite permise pour l'eau potable en Ontario, s'alimentent dans une proportion de presque 60 p. 100 dans ces zones à risque élevé. Pour remédier à la situation, il faudra mettre en oeuvre des programmes qui encouragent la modification des pratiques actuelles de gestion des nutriants.

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Introduction

In some agricultural areas, the application of natural and commercial fertilizers combined with livestock, septic tank and atmospheric inputs contribute to nitrate contamination of groundwater (Novotny and Chesters, 1981; Spalding and Exner, 1993). Particularly in landscapes underlain by permeable glacio-lacustrine materials, agricultural fields are the main diffuse sources of nitrate that is leached to groundwater (Hill, 1996; OMAFRA, 1994; Jones, 1975). The maximum downward movement of nitrate occurs when soil is near saturation but other critical factors such as soil type, climate and tillage methods, as well as fertilizer type, timing and application rates will influence nitrate transport (Ryan, 1994; OMAFRA, 1994).

In the Regional Municipality of Waterloo, groundwater is the main source of drinking water for the cities of Waterloo and Kitchener, rural communities and private homes. Although surface water sources such as the Grand River augment water supplies, groundwater represents over 90% of the Region's total water supply (CG&S, 1996). The Region of Waterloo supports one of Canada's richest agricultural communities, where farmers represent 5% of the population but use over 75% of the land base. Agricultural lands in the Region support seven main crops (Terraqua, 1995c) which are located on soils ranging from coarse-textured gravels and sands to impermeable clays (Presant and Wickland, 1971). Nitrogen application rates in the Waterloo Region range from 60 to 130 kg/ha/yr depending on crop type (CG&S, 1996). Estimates of total rural non-point source nitrogen loads to groundwater within the Region range from 604,000 to 2,520,000 kg yr^{-1} (CG&S, 1996).

Nitrate contamination of the Baden Municipal Well Fields provides an example of how current agricultural practices throughout the Waterloo Region have affected the quality of groundwater for drinking purposes. The community of Baden has historically obtained the majority of its water from a thick, laterally extensive aquifer with a regional recharge zone located north-east of the well fields in the Waterloo Moraine. However, nitrate contamination of this aquifer has recently forced the closure of these wells. Nitrate-N concentrations in groundwater range from 1.5 mg L^{-1} to a high of 19.0 mg L^{-1} and are distributed over an area approximately one km^2 (Terraqua, 1995b, 1995c). Sections of the aquifer in the recharge zone overlain by permeable sand and gravel generally show nitrate-N concentrations that exceed the provincial water quality guideline of 10 mg L^{-1} (Terraqua, 1997). If ingested at high enough concentrations, nitrate may cause adverse health effects such as methemoglobinemia (blue-baby syndrome) or cancer (Keeney, 1986). Nitrate leaching through soils from the application of manure and fertilizer is suspected to be the major source of nitrate contamination in the Baden wells (Terraqua, 1995b).

The objectives of this paper are to identify the distribution of nitrate contamination in the capture zone of the Baden Municipal well fields and assess the risk of agricultural land use on nitrate contamination of the Baden, Wilmot, Mannheim West and Erb Street well fields.

Methods

Study Area

The study area is located in the Waterloo Region of Ontario, west of Kitchener-Waterloo (Figure 1). The area consists of soils predominantly from the Huron-St.Clement, Bennington-Bookton, Burford-Fox, Brant-Waterloo and Organic associations (Presant and Wickland, 1971). The Waterloo moraine is a glacial landform deposited during the latter part of the Wisconsian ice age (Karrow, 1993; Terraqua, 1995a) that consists of complex depositional units of ice-contact and glacial outwash sands and gravels, separated by silt- and clay-rich tills (Terraqua, 1997, 1995a). The moraine is a multi-aquifer system with three main aquifer units divided by three aquitards (Terraqua, 1995a; Paloschi, 1993). The main pumping aquifer consists of an extensive sand and gravel unit that supplies eight municipal well fields with water (Terraqua, 1995a). The Waterloo moraine is the main source of recharge for this aquifer (Terraqua, 1995a). The surface topography throughout the study area is hummocky and land use is predominantly agricultural (GRCA, 1997).

In the study area, the approximate groundwater flow direction, locations of production wells and concentrations of nitrate in groundwater are shown in Figure 1. For the Baden recharge area, groundwater flows to the southwest in a predominately horizontal direction (hydraulic gradient <0.001) towards Baden (Terraqua, 1995a). Estimates of groundwater flow

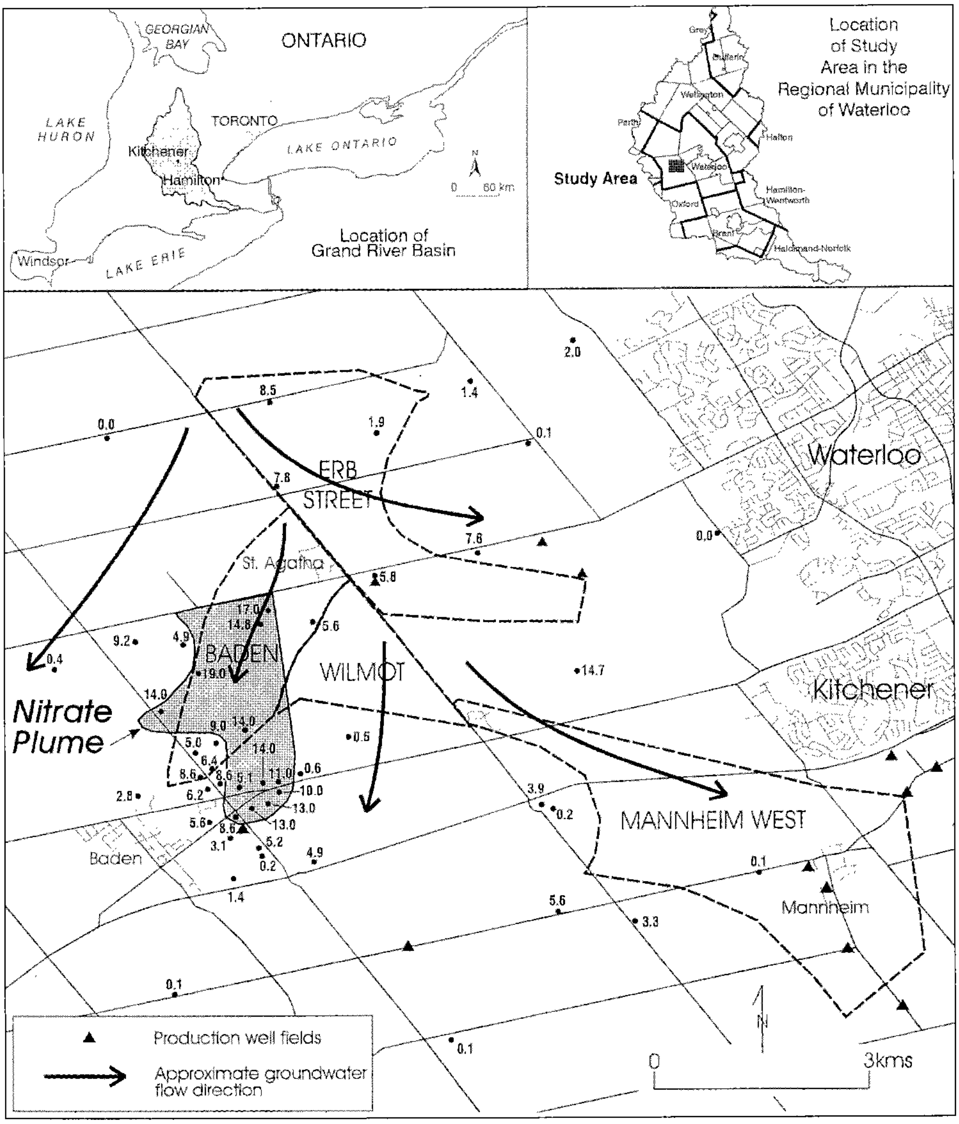

Figure 1: Study Area

velocities range from 10 to 100 m yr^{-1} (Terraqua, 1995a). Regional groundwater recharge to the well fields originates from a large section of the Moraine located to the west of St. Agatha (Terraqua, 1995a). The presence of shallow fine-grained soils near the well field limits local recharge (Terraqua, 1995a). The Baden wells are pumped at low rates (30 L sec^{-1}) and produce limited groundwater drawdown due to the transmissive nature of the aquifer (Terraqua, 1995a).

The unions between capture zones and recharge areas, (hereafter referred to as well recharge zones) were used to compare risk ratings for the Baden, Erb Street, Wilmot and Mannheim West well fields (Figure 1). The choice of well fields for this study was based on the physiographic and land use characteristics of the area and the availability of groundwater nitrate data. In the study area, nitrate-N concentrations in groundwater range from less than 0.1 mg L^{-1} in some areas to a maximum of 19.0 mg L^{-1} (Figure 1). The majority of high values are found near the Baden well fields. The extent of nitrate contamination in this area is shown in Figure 1 as a glove-shaped plume contoured to 10.0 mgL^{-1} nitrate-N (Terraqua, 1995c).

Data Sources and Analysis

Hydrochemical data were obtained from the following government documents and consultant reports.

- Groundwater chemistry was sampled from monitoring and production wells by Terraqua (1995a) in July 1993, February 1994, and in 1996 as part of a separate study of the Baden area (Terraqua, 1997). These data combined with pumping tests were used by the consultants to delineate capture zones and recharge areas for nine well fields (Terraqua, 1995a).
- Nitrogen application rates for Wilmot Township were estimated by consultants using a combination of 1991 Statistics Canada Census of Agriculture data, discussions with stakeholders familiar with agricultural practices in the Region of Waterloo and a review of available literature. The estimates were generated from 1983 1:50,000 land use system

Table 1: Land Use Systems and Nitrogen Application Rates in the Waterloo Region (adapted from CG&S, 1996)

Land Use	Description	Total Nitrogen Loading* (kg/ha/yr)	Risk Category
Continuous row crops	100% row crops (50% beans, 50% corn)	127.6	High
Corn system	60% row crop, 20% small grain, 20% hay	102.3	High
Mixed system	33% row crop, 33% small grain, 34% hay	85.0	Moderate
Grazing system	100% fair pasture	78.3	Moderate
Grain system	90% grain, 10% hay	77.0	Moderate
Hay system	70% improved hay, 30% improved pasture	71.9	Low
Pasture system	70% fair hay/pasture, 30% good hay/pasture	63.4	Low
Built-up	Built-up areas	0	Low
Woodland	Forest cover with a minimum of 45% crown closure	0	Low

*average for Wilmot Township

data provided in digital format by the Ontario Ministry of Food, Agriculture and Rural Affairs (OMAFRA).

A description of land use in Wilmot Township and estimated nitrogen application rates are presented in Table 1. For purposes of analysis, individual land use application rates were grouped to produce three categories of risk: high (100–150 kg/ha/yr), moderate (75–99.9 kg/ha/yr), and low (0–74.9 kg/ha/yr). In a review by Baker and Laflen (1983), a linear relationship between nitrate-N losses below the root zone and nitrogen application rates was found to occur at annual rates above 50 kilograms per hectare.

There was some concern over the validity of relating nitrogen application rates based on 1983 land use system data with groundwater nitrate-concentration data from the mid 1990s. However, since nitrate contamination of groundwater is a function of present and past land use practices (Johnston, 1994), the use of the older data set is justifiable. Significant changes in land use since 1983 could bias the results of risk assessment. Although a thorough examination of these changes was not included in this study, a roadside survey conducted in the north east corner of Wilmot township by Ecologistics in 1993 (CG&S, 1996) showed that the overall pattern of land use was similar to that shown in the 1983 OMAFRA map.

Soil drainage information provided by CG&S (1996) for the Region of Waterloo was used to approximate the infiltration potential for nitrate contaminated water to move through the unsaturated zone into the groundwater. Deep drainage was calculated by dividing the annual deep drainage volume (mm) by the annual precipitation (932.9 mm) averaged over a 10 year period from 1983 to 1993. Annual deep drainage volumes were estimated with a water balance model called HELP (Hydrological Evaluation Landfill Performance) using soil texture, soil thickness, porosity and water holding capacity as model inputs (CG&S, 1996). Deep drainage ratings were combined with digitized soil series data from Agriculture Canada at a scale of 1:20,000 to develop GIS coverage for three potential risk categories of soil drainage: low, medium and high. Built areas were included in the low category.

Spatial analysis of data for this study was performed using ArcView and ArcInfo, two mutually compatible, vector based Geographic Information System (GIS) software packages. Deep drainage and nitro-

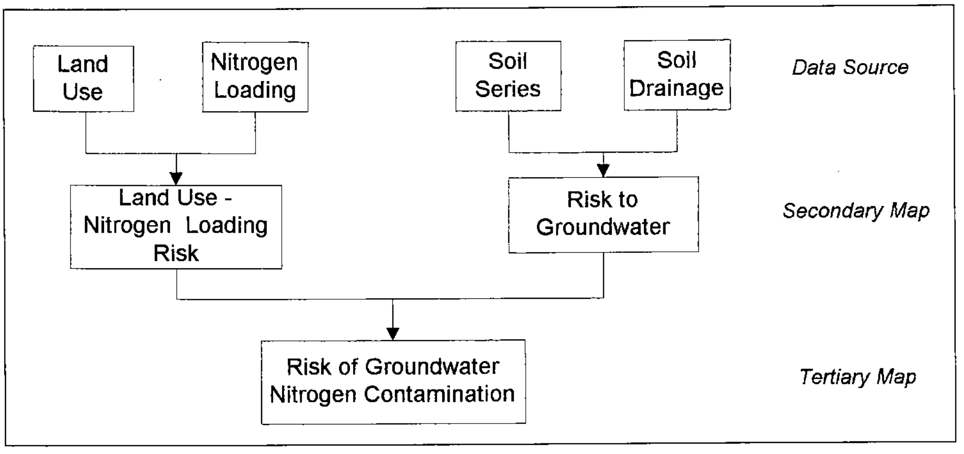

Figure 2: GIS Map Layer Sequencing used to Determine the Risk of Groundwater Nitrate Contamination

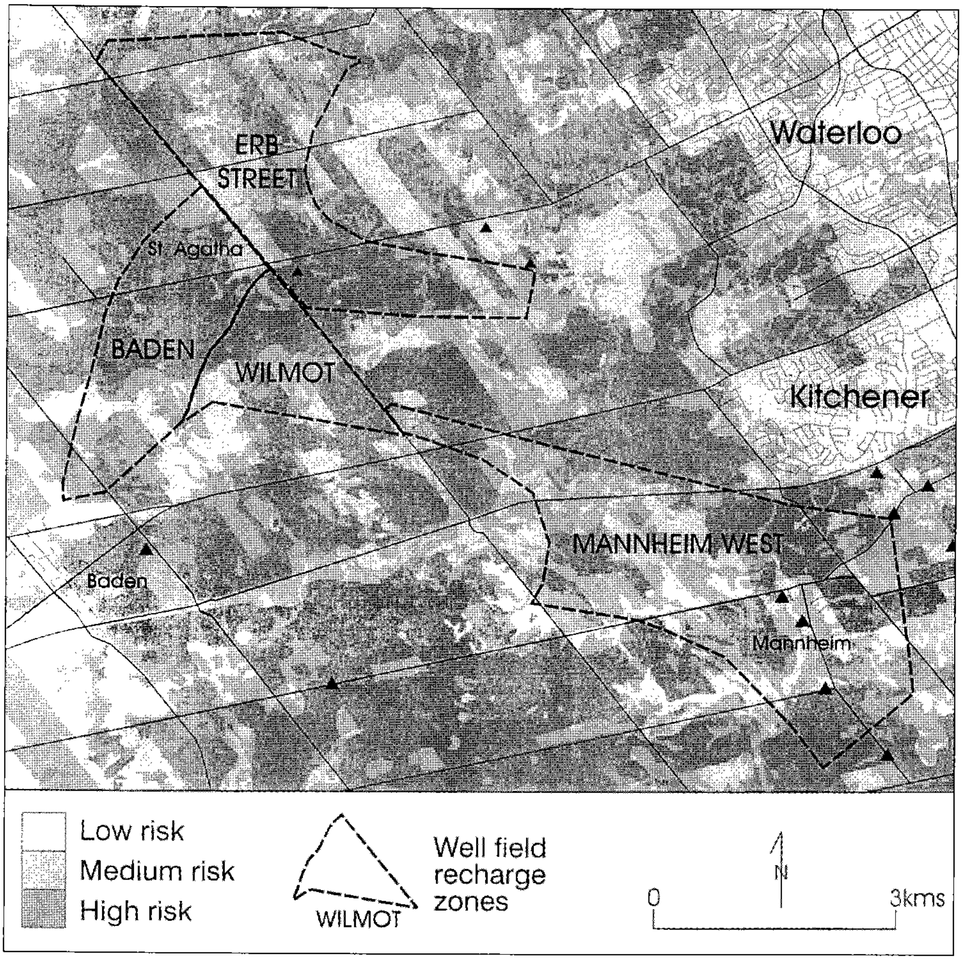

Figure 3: Risk Map

gen loading coverage were combined to produce a final coverage illustrating the potential risk to groundwater associated with both. The layer sequencing is shown in Figure 2 and the final risk map indicating areas of high, medium and low risk is presented in Figure 3. The respective contributions of deep drainage and nitrogen loading to the final risk map are provided in Table 2.

Results and Discussion

With the exception of one monitoring well south east of the Erb Street recharge zone, groundwater nitrate-N concentrations are highest near the town of Baden, as indicated by the glove-shaped plume shown in Figure 1. Of the four well recharge zones compared in this study, Wilmot and Baden are at the highest potential risk based on soil drainage and nitrogen loading data for these regions (Table 2 and Figure 2). The higher risk rating relative to the Mannheim West and Erb Street recharge zones can be attributed to hydrogeological conditions and higher nitrogen application rates required for corn in the Wilmot-Baden recharge areas. Approximately 66% of the Wilmot well field recharge zone falls into the high nitrogen loading category, compared with

Table 2: Risk of Groundwater Nitrate Contamination for the Study Area and Four Well Field Recharge Zones

Risk Categories	Risk Ratings	Well Field Recharge Areas				Total Study Area (% area)
		Baden (% area)	Erb Street (% area)	Wilmot (% area)	Mannheim West (% area)	
Deep drainage	Low	19.9	12.1	18.5	16.6	24.7
	Moderate	21.5	35.1	28.2	32.7	29.1
	High	58.6	52.8	53.3	50.7	46.1
Nitrogen loading	Low	22.5	38.3	30.1	36.7	37.6
	Moderate	29.1	19.1	3.9	28.8	18.6
	High	48.3	42.6	66.0	34.5	43.8
Risk: deep drainage and nitrogen loading combined	Low	13.3	19.6	16.8	20.1	27.3
	Moderate	28.0	31.7	24.8	39.1	30.1
	High	58.7	48.7	58.5	40.8	42.6
Soil associations						
Huron-St. Clements		16.4	4.2	8.2	19.1	12.9
Bennington-Bookton		4.0	1.2	7.8	12.3	9.6
Burford-Fox		40.7	7.6	17.3	32.9	28.4
Brant-Waterloo		37.0	85.0	59.9	30.1	41.9
Organic		1.4	0.8	3.6	3.9	2.9
Other		0.4	1.2	3.2	1.8	4.2
Total area (hectares)		472.9	787.3	255.9	1130.2	1216.9

48.3%, 42.6% and 34.5% for the Baden, Erb Street and Mannheim West recharge zone, respectively. Despite lower nitrogen loading rates, risk in the Baden recharge zone is similar to that of Wilmot because of better soil drainage properties.

The surficial geology of the Region may be an important factor in explaining contaminant levels in each of the four well fields. The Baden, Wilmot and Erb Street well fields are separated from their respective recharge zones by a clay cap at or near the surface (CG&S, 1996). Clay aquitards are quasi-impermeable and reduce the infiltration of nitrate-contaminated recharge water from high risk farmland in the surrounding area, and increase the distance over which contaminated groundwater must travel to reach the production wells. Migration of the glove-shaped nitrate plume beneath the aquitard over the Baden production well has resulted in steadily increasing nitrate contamination since 1983 (Terraqua, 1997). Mannheim West wells have low nitrate concentrations because they exist in an area of comparatively low risk. Wilmont and Erb Street well fields maintain nitrate levels below the drinking water limit but at estimated recharge rates ranging from 0.20 to 0.35 m yr^{-1} (Terraqua, 1995a,b,c), combined with increased hydraulic gradients caused by pumping, nitrate contamination may be imminent in the future.

While soil drainage and fertilizer application rates are important controls on groundwater nitrate contamination, other site specific factors such as tile drainage and livestock production are also important. Data compiled by Kanwar *et al.* (1983) show that almost 50% of fertilizer-N applied to the soil in Iowa is discharged to stream channels or drainage ditches by tile drainage water. This may not be a significant consideration in high risk areas with good natural drainage because it is less likely that tile drains would be installed in these areas. A more important source may be large feed lot operations where nitrates from barn yard wastes and manure storage ponds leach to groundwater. While it is difficult to distinguish between nitrate contributions from variable sources, evidence from studies on groundwater quality indicates that animal wastes from active or abandoned feed lots may be a significant source of nitrates to groundwater (Kirder, 1987).

Results of this study suggest that all of the wells supplying drinking water for the Region of Waterloo are at risk. Since 1983, groundwater nitrate-N concentrations near the town of Baden have gradually increased which is not uncommon in many agricultural areas (Halberg, 1989). Detailed hydrochemical investigations have not been conducted for other well fields, but it is reasonable to expect that a similar phenomenon may be occurring at these sites. Programs directed towards changing current nutrient management practices must be instituted if this trend is to be reversed.

Conclusions

The major factors contributing to groundwater nitrate contamination on a regional scale are the application of nitrogen-based fertilizers to agricultural land, and the potential of soils to leach nitrate to groundwater. Assessment of potential risk associated with these two factors indicates that 43% of the total study area and 41–59% of the four well field recharge zones chosen for analysis fall within the high risk category. While the highest levels of groundwater nitrate contamination are found in the Baden area, our results suggest that over time other well fields may be at risk.

Long-term solutions to this problem must involve farmers as key actors in the planning process. Examples of 'Best Management Practices' that are both acceptable to farmers and have reduced groundwater pollution include nutrient management strategies (controlled fertilizer application, construction of manure and silage storage facilities), well head protection, and retirement of high risk agricultural land (Supalla *et al.*, 1995). It is critical for the farming community to be actively involved in the design, adoption and implementation of these nutrient management strategies in order to protect the long term health of the region's water supply.

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