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Wellhead Protection Strategies: An Agricultural Perspective

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* This version is intended for discussion only and not for publication.

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1.0 INTRODUCTION

This paper will examine wellhead protection strategies, with an eye to agriculture's role. A key focus will be on the implementation of a multiple barrier approach to water protection, which includes factors such as proper well siting, construction, and maintenance. The paper discusses some of the most critical elements to protecting our water supply, in a manner that should be accessible for readers with a basic knowledge of water supplies. While much of the research quoted was examining private wells for rural residents and farming operations, similar principals apply for municipal wells, but higher standards and stricter enforcement are necessary as these wells typically draw significantly larger amounts of water and thus may draw water and contaminants from a larger area. This paper will provide a brief outline of the prevalence and importance of agriculture to Ontario. The remainder of the paper focuses on different aspects of groundwater and water wells in Ontario. The regulations governing Ontario's water supply, approaches to protecting the drinking water supply, which includes a thorough examination of the key factors to a multiple barrier approach, abandonment of wells and agriculture's role in protecting drinking water supplies are discussed in detail. Some general recommendations and conclusions will also be provided.

A tragic event, as that which recently took place in Walkerton, brings attention to the importance of our natural water supplies. Following such an incident, it is important that answers be sought not only of the incident itself, but of the structures and guidelines that allow such an event to occur. Groundwater is a precious resource that can provide clean and pure water for a significant portion of the population, but it must be better protected if it is to do so long into the future. To access groundwater it is usually necessary to install a water well; it is ironic that this same act can also be a cause of serious contamination of the water source. Proper water well construction and maintenance is one of the most critical elements in protecting groundwater supplies. An improperly constructed well is an open passageway that can transmit contaminated waters directly into aquifers. Given the importance of proper construction and maintenance, it is surprising that greater attention is not given to discussing and researching the practices in Ontario.

The events in Walkerton have also drawn a great deal of attention to the issue of wellhead protection. Well 5, the well attributed as the most likely point of entry of contaminated water in Walkerton, was considered unsuitable for a long-term municipal drinking water supply when constructed and wellhead protection measures were recommended but not implemented. There are many potential sources of contamination through industry, municipal operations (i.e. sewage treatment facilities) as well as agricultural operations. It is unrealistic to think that agriculture or any other industry will be relegated to only the most isolated locations or that landowners will happily donate or sever lots from their property or alter land-use practices without adequate compensation. Wellhead protection is an important component of ensuring safe water supplies and clean aquifers. In environmental and financial terms, it costs far more, up to 200 % more, to clean up a seriously contaminated aquifer or to find an alternate water supply than to carry out protection measures. Any strategy imposed to protect water supplies must be reasonable, justifiable and scientifically based.

2.0 AGRICULTURE IN ONTARIO

Ontario is home to the largest and most diversified part of the Canadian agriculture and food industry, and the Ontario food sector has been a thriving part of the Ontario economy. With $7.2 billion in sales of more than 200 commodities in 1999, Ontario farmers continued to demonstrate their good management skills and strong business sense. The size and scope of Ontario's agriculture and food sector are most impressive when viewed in the context of the overall Ontario economy and the national agriculture and food industry. Consider the following statistics from 1999:

i) The agri-food sector contributed $23.5 billion to Ontario's GDP, almost eight percent of the provincial total.
ii) The Ontario agri-food sector employs nearly 680,000 people, or approximately 12 percent of the total employed labour force in the province.
iii) Primary agriculture accounts for 16 percent of the total agri-food labour force.
iv) Ontario-based agri-food goods producing industries account for 38 percent of Canada's GDP from the agri-food goods production sector.
v) Ontario farmers produce 26 percent on Canadian agricultural output in terms of GDP.

Census data indicate that agriculture represents a source of income for more than 130,000 rural residents. Further, 31 jobs are created for every million dollars of output in agriculture and related services (19 direct and 12 indirect). Clearly, agriculture is very important to maintaining and increasing employment in rural Ontario.

3.0 GROUNDWATER AND WATER WELLS IN ONTARIO

In general, groundwater quality in Ontario is good to excellent. A thriving bottled water industry is a witness to this. Approximately 25 % of the population is dependent on groundwater as their source of drinking water (100 % in most rural areas) and this population is growing. The annual population growth rate of Ontario is approximately 200,000 people. Of this, approximately 40,000 people are located in rural areas, which translates into the need for approximately 10,000 new wells to supply the increased population with potable water. In addition to the increased population in rural areas, there are other demands on the water supply, for agricultural and industrial purposes, as well as recreational. There are also that many more lawns and gardens to be watered. This could place a significant strain on the water system.

In addition to the problems of increasing demand there are some serious concerns related to contamination of the groundwater supply. This could come from a number of sources, including inactive waste disposal sites, land contaminated from industry and spills, underground storage tanks, agricultural sources, or abandoned and inappropriately managed wells (water, gas and oil wells).

Aquifers, defined as strata of the overburden or bedrock that both store and transmit waters, are the primary sources of groundwater water supplies. Those aquifers that are closest to the surface or are most effectively connected to the surface are the most susceptible to contamination.

Contaminants in groundwater broadly fall into one of three categories (Jaffe and Divino, 1987). These are *mineral/metal contaminants* – including man-made or naturally occurring inorganic chemicals; *Microbial contaminants*- including bacteria, viruses, and parasites; and *synthetic organic chemicals*-including gasoline, pesticides, and other chemicals widely used in businesses, homes, industry, recreation, and agriculture. Each of these contaminants can pose health risks to humans.

Considering a surface environment where most natural waters have significant levels of bacteria and sometimes troublesome levels of other contaminants, groundwater remains surprisingly free of contamination. The reason for this is the ability of the earth to remove contaminants as the water percolates through it. As water percolates through the unsaturated zone (the layers of soil and sediment above the water table) a process of attenuation takes place whereby many contaminants are removed from the water. The most significant of these processes are filtration, sorption, oxidization and reduction, and biological decay. Other processes of attenuation include dilution, buffering, chemical precipitation, volatilization, evaporation, and radioactive decay (see Jaffe and Divino, 1987 for further explanation of these processes). These processes continue to operate within the saturated zone, albeit far less effectively.

The processes of attenuation are greatest in soils and unconsolidated sediment of low to moderate permeability (clays through sands). Unfractured bedrock of limited permeability such as limestone and sandstone also has significant attenuation processes operating within them. Fractured bedrock and highly permeable unconsolidated sediments (i.e. gravel) have very few of the attenuation processes occurring and can result in contaminants moving relatively freely.

Strategies for choosing and protecting aquifers for water supply must take these physical factors into consideration in identifying recharge areas and protecting them from activities that will result in the water that is recharging becoming contaminated.

3.1 Regulations governing Ontario's Drinking Water Supply

Water is under the jurisdiction of the provinces under the Constitution Act (RSC 1982), the exceptions being transboundary water and water as it relates to the federal government's responsibilities to first nation peoples. In Ontario the primary legislation governing groundwater is the Ontario Water Resources Act (RSO 1990). It sets out the authority of the province and identifies the role of the province in regulating and managing the use of the resource. Use of groundwater is regulated with "Water-Taking" permits issued to a user in specific quantities and purposes. The responsibilities of the user municipalities, corporations and private individuals are also set out in this Act. In the document Ontario Water Response (May 2000) there is a summary of legislation as it relates to water quality, water quantity and land use as it relates to water quality.

Municipalities are charged with the responsibility of assuring an adequate supply of drinking water and with the treatment and disposal of wastewater for the municipality (Municipal Act, RSO 1990). In cases where the municipality draws its water from groundwater, a well or well field is established from which the water is to be drawn. The wells require permits from the province and their construction and operation is subject to standards set out under the Ontario Water Resources Act (RSO 1990).

Water well construction in Ontario is regulated by the Ministry of the Environment, primarily under Section 903 of the Ontario Water Act. Water well contractors in Ontario are required to be licensed and to renew that license annually. Enforcement of water well regulations is carried out by water well inspectors on a customer complaint basis. This is a somewhat limited process as post case evaluation is very difficult since the bulk of workmanship is buried deeply underground.

All land use activities can result in the generation of adverse effects on water quality. The concern that is paramount is to identify what practices are most detrimental and what mechanisms are appropriate for the management of water quality. The principles that have been set out by the province are found in Section II of the Comprehensive Policy Statement (1996).

Contamination of groundwater is controlled by the Ontario Water Resources Act. (RSO 1990) This Act together with the Environmental Protection Act (RSO 1990) provides for prosecution of those who pollute this resource. They do not however provide for the precautionary protection of the resource in general, but rather provide a regulatory punitive basis for responding to incidents of pollution. Under the Planning Act and under the Comprehensive Policy Statement there is the opportunity for the development of proactive protection of aquifers.

The provincial interest in groundwater and water supply is covered under Part 1 section 2 (a), (b), (c) (e) (f) (g) of the Planning Act. This is further elaborated under section 2.4.1 of the Comprehensive Policy Statement (1996).

"The quality and quantity of groundwater and surface water and the function of sensitive groundwater recharge/discharge areas, aquifers and headwaters will be protected or enhanced."

This statement of provincial interest establishes the opportunity for municipalities to undertake the protection of aquifers. The mechanisms for such protection are of a wide variety depending on the approach that the municipality takes.

The municipality may request that the director of Water Resources (OMOE) designate an area a "water supply area" (under the Water Resources Act Section 33.1) This section has most often been applied to water supply reservoirs and their immediate area. It prohibits bathing and swimming, prohibits the presence of materials that may cause impairment of water quality and prohibits water takings that may interfere with the municipal supply. This section can be applied to water supply watersheds and thus can provide protection to aquifers. The application to a watershed is primarily aimed at restricting land uses that are associated with toxic compounds (industry) although in some cases all but the most benign uses are prohibited including agriculture, roads, residences and commercial forest harvesting. The cities of Halifax and Vancouver have protected water supply watersheds.

Official Plan policies are enabled under the Planning Act (1990) and the Comprehensive Policy Statement to set out local policy that would identify sensitive recharge and discharge areas so that they can be protected from the adverse impacts of land use and development. Today these measures are increasingly being adopted (Region of Waterloo, Halton Region, County of Wellington, Ottawa Carleton and others). For the most part, these policies are used to guide decisions on amendments, minor variances and development applications. In a few cases, they are being used as the basis for the passing of restrictive bylaws, and in the case of the Region of Waterloo a proposed zoning for protection of groundwater aquifers. (This zoning is primarily aimed at industry and intensive use of land that can cause contamination.)

There are several approaches to zoning for water protection. These include restrictive zoning that is focused on a water supply area as a special planning area. Another approach is performance zoning that establishes the level of performance required for all land use activities. It is used to limit pollution loadings placing the onus of achieving the standards on the land user. Yet another approach is land use zoning that identifies permitted land uses on aquifers, prohibiting those that could result in the contamination of the aquifer. This later approach does not allow for innovative practice and management that can mitigate potential adverse impacts.

Well fields are areas of land containing one or a group of wells that provide drinking water to a public water supply system. In some cases the well field includes not only the area of influence of the wells but also the catchment area, which contributes to the wells. The catchment area, in many cases, does not correspond to a topographic watershed. Rather it is encompassed by the lines of flow from the area of recharge to the zone of the well's influence on the water table (draw down cone).

Municipal wells are often located on small parcels of property in the countryside. These parcels are large enough for the well, well house and a small service and access area. The area of the aquifer from which the well draws water underlies other property, which in most cases is not owned by the municipality. As a result land use on the land adjacent the well has the potential to impact water quality, and the municipal well may impact upon adjacent private wells and surface waters as a result of the draw down. Control of land use in the well field is often required and may be accomplished through several mechanisms.

In some cases municipalities seeking to protect the well field acquire the land adjacent to the well. The means of acquiring the appropriate land for the protection areas has also varied from land donation, conservation easement, public education to tailor land use activities and land acquisition. In some cases this can protect the well field (City of Guelph, Arkell well field). Land acquisition is the most effective mechanism and is also most equitable since compensation is provided through the purchase of the land. It is also the most effective approach when the well field is located in an adjacent municipality. This is often the case for urban municipalities and rural towns.

A second approach is to designate the well field as a special planning area and apply restrictive zoning. A uniform zoning is often applied within the draw down cone. In the case where the well field is defined by the catchment area a series of zones are designated which have increasingly restrictive requirements as they are closer to the well head. The national Rivers Board in U.K. and the Province of New Brunswick utilizes a three zone approach for well field and aquifer protection.

In the United States and other provinces, several methods have been used to define wellhead protection areas. These strategies can be as simple as selecting an arbitrary or calculated fixed radius, where no site-specific information is incorporated. The next level of complexity would involve selecting a variable shape, which would include some site-specific information. In some areas, zones of influence are modeled using analytical or numerical methods that predict zones of influence based on several hydrologic parameters. The most reliable and most time-consuming and costly selection method would be hydrogeological mapping of the aquifer. These zones are most often mapped out based on the time of travel that it takes for water to move to the well under normal water extraction rates. The use of time of travel zones is based on the assumption that the closer to the well a contaminant is introduced the less likely that it will be diluted or assimilated by the processes operating in the aquifer (adsorption, bio-degradation, decomposition etc.). New Brunswick divides their zones as having travel times of 100 – 250 days, 250 days to 5 years and 5 to 25 years. The approach is based on the level of risk associated with different activities and the nature of contaminants, which have different rates of movement and persistence in the environment.

According to the Golder hydrogeological report assessing Walkerton's wells, a two-year time of travel is commonly adopted in wellhead protection area management programs for the location of sentry wells. Golder used a groundwater modeling technique that incorporated several site-specific hydrologic parameters such as hydraulic conductivity, transmissivity, thickness of active flow zone, porosity, and hydraulic gradients. This firm performed a 36 hour pumping test monitoring quality and water levels in Well 5, 12 test wells, nearby private wells and surface water monitoring points. This allowed an estimate of the 30–day zone of capture, which was then extended to a 2 year zone of capture by looking at well-driller records and mapping the aquifer. The result was the wellhead protection area would involve restriction/purchase of a strip of land extending 3 km south-west from Well 5. How many municipalities could afford (either politically or financially) to acquire this amount of land around its wells? This is only one of 7 wells serving a small community (only 3 were operating at the time, however the other wells were not retired properly therefore any protective zones would have to be maintained to ensure integrity of the aquifers) and this model did not account for the infiltration process or other surface influences which played a large role in the extent of contamination entering Well 5 during May 2000.

In some cases where the hydrogeology is simple and the sources of water can be well defined, protection of recharge areas is undertaken. The US EPA has develop an approach to protection of such areas through the sole source Aquifer Designation process which is used for protecting well fields and aquifers as sources of drinking water. (USEPA, Office of Ground Water and Drinking Water, 1998) This does not occur frequently in southern Ontario due the complexity of our surficial geology and the uncertainty as to the linkages between the surficial aquifers and the bedrock aquifers. In southern Ontario the major recharge areas tend to be the sand and gravel glacial outwash deposits, the moraines and the areas where depth to bedrock is shallow.

4.0 PROTECTING THE DRINKING WATER SUPPLY

Protecting the drinking water supply requires a multi-step process that, if implemented correctly, will provide multiple barriers to contamination affecting the population drinking this water. It begins with a good wellhead protection program. This will reflect an understanding of the site-specific vulnerabilities including potential contaminants, their mode of transport, and groundwater and surface water influences in the area. Appropriately siting, monitoring, constructing and maintaining the well with these vulnerabilities in mind is essential to protecting the drinking water supply. Climatic factors, land use patterns, vegetative cover, topography, soil and geological characteristics may all affect contaminant transport and residence in groundwater. The condition of a well, location of potential contaminants, and land-use management practices must also be considered.

4.1 Siting and Monitoring

Conboy and Goss (2000) show that any well type can be poorly located and vulnerable to contamination. Conversely, properly sited, constructed and regularly maintained wells are more resistant to contaminant influx. It is important to know a well's history of contamination and to understand local groundwater flow patterns, so that contaminants are not flowing directly to a drinking water well.

4.1.1 Groundwater flow patterns

Understanding the local flow of groundwater may be the most critical tool that can be used to predict the susceptibility of a well in a given location. The groundwater flow patterns can be estimated by looking at the general topography of the site and local area, and by looking at flow in nearby streams or creeks. Water tends to flow downhill and groundwater tables tend to follow the slope of the land. However, on some properties the area surrounding buildings may be built up on a local elevation, small hills immediately surrounding buildings may reflect disturbances from the construction of the house and may not reflect the slope of the groundwater table.

Hydrogeological studies can be used to define the groundwater flow patterns using test wells, tracer studies and monitoring surrounding surface and groundwater features. This type of detailed analysis should be conducted in siting municipal wells. If groundwater flow patterns are understood prior to well construction, a suitable site where contaminants flow away from the well, along with an appropriate well design and maintenance schedule, can be developed.

It is essential to monitor a well's history of contamination. This is an important tool in understanding well susceptibility. The type, frequency, and magnitude of contamination events affecting well water must be implicit. If the well has exceeded drinking water objectives frequently for the same parameter, it is likely that there is a constant source of contamination entering the well. If the well is properly sealed and there is no debris in the well, the source is likely entering from the groundwater not the top of the well. All potential contaminant sources should be located downhill/downgradient from drinking water wells. This is true even if tile drains are present to direct most of the water in a different direction.

It is also important to understand if the well is supplied by water drawn from a confined or unconfined aquifer, the depth of the water table and factors present in the geology and soil profile that may contribute to contaminant migration. Unconfined aquifers do not have an impermeable layer at the top of the water table. These types of aquifers can be shallow and recharged rapidly from precipitation events. The melting snow or running water transports material from the soil surface deep into the soil towards groundwater. Movement of contamination follows the same pathway. This makes unconfined aquifers more influenced by surface activities and more prone to contamination. Well water should be monitored carefully after repairs, heavy precipitation, and during the spring thaw. Susceptibility of aquifers to contamination is also impacted by the hydrostatic gradient (slope of the water table or pressure gradient in the aquifer). Where gradients are steeper water moves faster. Thus the movement of recharge water is more rapid and is more susceptible to contamination. Testing water at times when the potential for contamination is higher will provide the most accurate assessment of how secure the water supply is. Personnel responsible for maintaining the integrity of a municipal supply should be made aware of the potential risk associated with these events. It is also important to assess water quality if contamination is suspected due to a change in color or odor of the water, or due to continuing gastrointestinal illness.

4.1.2 Soil and Geological Influences

Results from groundwater quality studies in Ontario, (Goss *et al*., 1998; Raina *et al*., 1998; Conboy and Goss, 1999) showed that the majority of samples taken over a five year period from some drinking water wells were consistently contaminated with bacteria, whereas samples from other wells were free of such contamination. Conboy and Goss (2000) investigated the impact of profile stratigraphy in relation to well water contamination. Certain geological profiles or soil horizons may provide the ideal environment for bacteria and other contaminants to move to groundwater through the presence of conditions that promote the survival of bacteria, or through development of preferential flow paths that enhance their transport.

Wells in Ontario vary widely in their characteristics. They range extensively in the depth, either penetrating into underlying rock or being restricted to the weathering profile above the bedrock. The overlying soil can vary greatly and differ in respect to how likely it is to develop macropores. Different tillage practices can then determine how persistent these large pores can be. The underlying geology will affect the dominant soil type, and the viability of different land use practices, as well; some consolidated rocks are much more permeable than others. Some geological units contain many cracks, fissures and joints, or may have been significantly altered over geological time via folding, faulting, jointing or dissolution. These features may then act as preferred flow paths. This section provides an overview as to how soil type and geology could provide an indication of well vulnerability.

Several studies have looked at the distances that bacteria traveled in different soil types or in areas with different underlying geology. In aquifers that allow high pump rates, elevated concentrations of organic carbon and small amounts of clays or dissolved solids can enhance the movement of microorganisms. This is most pronounced in aquifers with a high degree of secondary pore structure, in which substantial portions of flow occur along preferred flow paths (Story et al., 1995; Malard et al., 1994; Allen and Morrison, 1973). Gerba *et al*., (1975) observed coliform bacteria to travel 0.6 metres in fine loamy sand and 830 metres in sand-gravel. Other studies have shown bacteria to move for more than 1 km in loamy sand aquifers (Harvey *et al*., 1989) and up to several kilometers in fissured karstic aquifers (Allen and Morrison, 1973; Malard *et al*., 1994; Gerba and Bitton, 1984). This shows that some geological environments may be too sensitive for groundwater wells to be treated as secure for municipal supplies without controlling surface inputs and/or treating water with filtration prior to chlorination.

Allen and Morrison (1973) found that the direction and rate of movement of contaminated groundwater through granitic and metamorphic rock units was mainly controlled by the direction of joints and fractures. Fracturing, dissolution and especially karstification, of limestone appeared to result in higher potential movement of bacterial contaminants through limestone rock than in any other geological formation.

In Ontario, wells that were more vulnerable to contamination were older, shallower, had water found at a shallower depth than low risk wells and had a shallower soil profile, as indicated by depth to bedrock. The majority of these vulnerable wells were also dug or bored construction (Conboy and Goss, 2000). The largest proportion of high risk wells were located in limestone or dolostone deposited during the Middle Ordovician period. This older material can be very weathered with large solution channels that have evolved through geological time.

Aquitards include shales, and thick clay deposits. Ontario also has many areas where there are continuous or intermittent layers of shale or hardpan layers. The shale present in the unit may be thicker or more continuous in some locations. These layers may offer some protection from bacterial transport to groundwater. They may act as an impermeable barrier, which restricts further vertical movement. Ontario wells that had a low risk of contamination were located in shale deposits more frequently than high-risk wells (Conboy and Goss, 2000).

Depth to bedrock appears to be another important factor affecting groundwater quality. If the depth of soil over the bedrock was shallow, there would be little opportunity for the soil to interact with water and any contaminants percolating with it. Consequently, a relatively unrestricted flow of water would take place, allowing contaminants to enter the groundwater. Bacteria have been shown to move through soil columns at pore velocities of 3 - 30 m/day in laboratory experiments (Wollum and Cassel, 1978; Smith et al, 1985; Fontes *et al.*, 1991) as well as in field studies (Harvey *et al.*, 1989; Harvey and Garabedian, 1991).

Conboy and Goss (2000) observed significantly more high risk wells on sites where bedrock occurs in the top 9 metres and fewer high risk wells on sites where sand or gravel/hardpan layers were found in the top 9 metres. This may indicate that in high-risk wells there is very little soil to filter any bacteria prior to the bacteria entering channels or cracks in the bedrock. Unconsolidated sediment or hardpan layers in the top 9 metres may offer some measure of protection. Hardpan may be impermeable, restricting water movement and the gravel is likely associated with coarse sand and clay, which may clog the pores and restrict water movement.

4.1.3 Soil Type

The soil provides a natural filtering action and adsorption site for the removal of bacteria and viruses. A study by Crane *et al.* (1980) found 92 to 97% of the bacteria irrigated onto soil were removed in the top 1 cm of soil. The extent of bacterial movement through saturated soil is mainly related to water movement, which is affected by soil properties. Smaller pore size, resulting from increased bulk density, may yield better filtration, as there is more soil available for adsorption along the same length of flow path. The diameter of connected pores also tends to decrease leading to a reduction in the rate of water flow through the soil. Van Elsas *et al.* (1991), and Huysman and Verstraete (1993) demonstrated a strong influence of soil bulk density on the migration of bacteria. Small (0.1 g/cm^3) increases in bulk density resulted in up to 60% decrease in transport of bacteria due to reduction in flow.

Analysis of the bacterial contamination in the Ontario Farm Groundwater Quality survey (OFGWQ) showed that well type, depth and soil hydrologic group were the significant determining factors (Goss *et al.*, 1998). Surface soil type has been shown to have a strong impact on the immobilization of bacteria from leaching or surface runoff (Crane *et al.*, 1983). Smith *et al.*, (1985) compared the movement of streptomycin-resistant *E. coli* through both undisturbed and repacked soils of different textures and found that bacteria moved furthest in coarse sand and least distance in fine sand for a given suspending solution. Burton *et al.* (1987) found a greater survival of *E. coli* and *Salmonella newport* in sediments of higher clay content. This was believed to be due to higher concentrations of organic matter and nutrients. Thelin and Gifford (1983) had similar results observing that topsoil provided a more favourable environment for fecal coliform persistence (7 - 20 days) than pasture or subsoil (2 - 6 days). Soil type can be important for contaminant transport because of structural factors such as pore size and continuity, and because of the potential for adsorption onto the surface of constituent particles. Sandy sites may restrict movement of bacteria through filtration (Crane *et al.*, 1983). This may offer some measure of protection to the well. The OFGWQ survey (Goss et al., 1998) observed bacteriological contamination was less in sandpoint wells, and a smaller percentage of wells on coarse textured soils were contaminated compared to wells on loamy soils. Conboy and Goss (2000) found that in Ontario, vulnerable sites were most likely to be located on clay soils. This may be due to the presence of macropores in clay soil, which would increase transport of bacteria into the well.

The clay and sand content markedly affect the structure of soil, its bulk density, permeability and its ability to adsorb water and cations from solution. All of these factors in turn influence whether bacteria can be transported through or survive in soil. Soils dominated by sand, especially coarse sand, have little capacity for water retention and drainage is rapid. There are few large aggregates or well-developed structural units. In most soils, clay particles readily form aggregates. Clay minerals also impart chemical and physical properties to soil that strongly influence its adsorption capabilities. This affects the availability of nutrients and the transport of bacteria. Clay soils that have poorly developed structure become waterlogged quickly whereas the networks of large interaggregate pores in well-structured clays can allow the soil to drain as rapidly as sands. Bacteria are often able to adsorb to clay platelets and may obtain nutrients or water from the clay. Clays may influence microbial survival indirectly through alteration of environmental factors such as pH, nutritional status, or directly through surface interactions. Clays also modify the survival of microorganisms by providing protection from UV radiation, desiccation, antibiotics, and predator-prey interactions (Marshall, 1980).

4.2 Construction of Wells

The water well industry in Ontario is made up of a large number of small to medium sized companies, many of which are family businesses with a long history of providing water to rural Ontarians. The majority of the wells constructed in Ontario are for farms and rural homes. Each of these wells acts as a water supply, but can also be a potential point for groundwater contamination.

There are three primary types of wells. **Drilled wells** can be completed in either unconsolidated sediment or bedrock. Drilled wells in unconsolidated bedrock require a screening mechanism to allow water to enter while keeping sediment out. Wells in bedrock generally do not require such screening as the bedrock is solid and stable. The diameter of drilled wells varies, but most new wells are between 100 millimeters (4 inches) and 200 millimeters (8 inches). **Bored wells** are most often completed in unconsolidated sediment and are of a large diameter (600 mm to 1000 mm.) These wells are primarily utilized to exploit low yielding aquifers. Their ability to collect and store water while not in use makes them an effective well in areas where smaller diameter wells could not function. Finally, **dug wells** are primarily constructed by hand or by equipment such as a backhoe. Very few new dug wells are constructed in Ontario, but a large number remain in use across the province. A particular concern about these wells is the poor standards to which they were constructed and the large number of them that may exist, but have been left abandoned improperly.

4.2.1 Water Well Construction and Contamination

The most critical element of water well construction is that the completed well does not result in a condition which would allow water to bypass these natural processes of attenuation and enter directly into the aquifer. In a sense, a water well is a puncture through the protective filter of the earth. Methods of proper casing and proper sealing of water wells guard against contaminants taking shortcuts to aquifers. A poorly constructed well cannot only become contaminated itself, but can contaminate the aquifer it draws upon and any aquifers that it passes through. It can also result in a contaminated aquifer passing contamination onto a previously uncontaminated aquifer.

The bulk of studies done on groundwater contamination have primarily only considered two variables of water well construction; those being *well depth* and *well type*. While these studies give important insight into the issue of well contamination, it can be difficult to interpret them fully as they fail to recognize the very important elements of well construction casing type, well maintenance, casing depth, and well sealing. Perhaps the most insightful of many of these characteristics is examining contamination ratios with the age of the well. Conboy and Goss (1999) demonstrated a significant correlation between well age and contamination. While this may be indicative of degradation of wells over time, it is far more probable that it is the result of improved construction practices that have been developed over time.

Another limitation of focusing on the variables of well depth and well type is that these choices are largely determined by the hydrogeology of the region. Water well contractors have a great deal more control over other variables in the process such as how they case wells, how they seal them, and how they finish them (landscape). Well owners have options regarding how they maintain their wells.

Both construction and the surrounding soil type influence contamination in wells. In an Ontario study, drilled wells were affected by the absence of loamy soils or soils rich in clay, whereas dug wells were most likely to be contaminated in clay soils (Conboy and Goss, 2000). The reason for these differences can be explained by preferential flow. Drilled wells are lined to depth, whereas dug wells do not restrict water entry and bacteria can move into such wells at any depth. The presence of a non-watertight well in a clay soil would allow surface water and surface contaminants entry into the well very rapidly through preferential flow paths near the soil surface, whereas sands may act to filter the bacteria. In drilled wells where the bacteria must travel to much greater depths, there is more interaction time with the soil and less chance of continuous macropores in clay soils. This can lead to adsorption of bacteria to the soil particles thus removing bacteria from further transport. Thick layers of clay, especially deeper compact layers, may be impermeable.

4.2.2 Casing

Casing choices for drilled wells primarily consist of plastic or steel casing. The minimum guidelines for casing wall thickness are set out in Ontario Regulations. The choice between plastic and steel is usually made depending upon the method of drilling employed and the type of equipment used by the contractor. Plastic casing has been the preferred material since the early 1990's unless the contractor is employing methods that will greatly stress the casing during construction (such as using a punching rig, a casing hammer, or an ODEX type system). Plastic casing has the advantage of being corrosion resistant, whereas steel casing can experience corrosion over time. Corrosion was noted in the case in Walkerton well number 7. Driscoll (1986) suggests that if steel casing is to be utilized in a corrosive area, greater casing wall thickness can be used to increase the durability of the well.

Casing depth is an important issue when considering protection against contamination. In the construction of a drilled well in unconsolidated formation the casing must extend to the well intake by virtue of the well design. In a drilled bedrock well, this is not the case. Once the well is drilled into firm bedrock, casing is not necessary to prevent the hole from collapsing (as the rock is solid and stable). Ontario regulations indicate that wells into bedrock must be cased to a depth of at least 6 meters unless the only useful aquifer is shallower and therefore requires less casing. This specification generally meets or exceeds the water well regulations in other regions (comparison was made with B.C., Montana, Utah, Georgia, and Illinois). Illinois regulations exceeded the Ontario regulation quite significantly regarding one consideration. In conditions where there is less than 30 feet (10 meters) of overburden (unconsolidated sediment) overlaying fractured bedrock, Illinois regulations require that a minimum of 40 feet (13 meters) of casing be installed. The Ontario regulations consider similar situations when discussing well grouting, but have no indication of requiring increased casing depth. It may be valuable to review this regulation and consider a revision similar to that seen in Illinois.

Bored wells in Ontario are typically cased with cement tile casing (also known as cement cribbing) although some water well contractors use galvanized steel casing. Summers (1999) reports upon some of the problems with the use of cement tiles, particularly the dangers of leakage through unsealed joints. Ontario regulations stipulate that casing joints in the upper 2.5 meters of the well be sealed, although there is no stipulation as to how this sealing should take place. Conboy and Goss (1999) note that bored or dug wells faced significantly higher rates of bacterial contamination than drilled wells. Similar studies elsewhere also demonstrate higher levels of total coliforms (bacteria) in bored wells than in drilled wells (e.g. CDC, 1998). It is argued in Summers (1999) that these higher rates are likely the results of improper sealing methods of cement tile joints or degradation of sealing over time, and that the diameter alone of the well makes it no more vulnerable to contamination than a drilled well of similar depth. Conboy and Goss (1999) also suggest that unsealed casing is a likely point of entry for contamination. Bored wells in the Prairie Provinces are regularly constructed with plastic or galvanized steel casing. While large scale studies have not been carried out to examine the water quality of these wells, the better casing joints and the much greater distance to the first joint (usually at least 6 meters) would theoretically result in a more secure well.

A second issue with bored wells is the very shallow depth of the aquifers that they make use of in some areas. Ontario guidelines allow for the construction of bored or dug wells of depths of less than 2.5 meters. While such wells may be necessary, special considerations should be made for regular testing if the well is to be used as a source of potable water.

Bored wells are an important source of water in many areas of Ontario. They are a very safe and effective way of exploiting groundwater resources provided that they are constructed properly. This includes the proper sealing and regular inspection of all casing joints in the upper portion of the well. There is some concern though that these practices are not always followed in Ontario. Contractors should be reminded of the importance of this practice and encouraged to ensure that they are complying with the regulations. Some may also wish to consider the utilization of different casing methods with longer distances between joints (galvanized cribbing or plastic casing.) Well owners need to be educated on the importance of regular maintenance.

4.2.3 Grouting of Wells

Perhaps the single most important aspect of well construction with regards to preventing contamination is the grouting (sealing) of the outside of the casing. When a well is drilled, the size of the borehole is greater than that of the casing. This means that there is space around the outside of the well (known as the annular space). If the annular space is not properly sealed during well construction, it can allow water to directly flow along the outside of the well and enter the aquifer without any attenuation of the contaminants it may contain.

A number of Ontario regulations apply to the sealing of annular space, but in general these regulations are of lower standards than regulations in other jurisdictions. Ontario regulations allow most wells to be completed with only 3 meters of sealing material. This is significantly less than the requirements give in other jurisdictions such as Montana (18 feet), Illinois (15-60 feet depending upon well depth), Alberta (entire length of casing above aquifer intake), or Utah (30 feet). Most of these regulations do make allowances where shallower aquifers must be tapped. A second area of concern in the regulation is the minimum size of the annulus. Ontario regulations suggest that the minimum size of the annulus should be 2.5 cm (a borehole diameter 5 cm greater than casing diameter). Regulations in other regions tend to have minimums of 4 to 5 centimeters. Driscoll (1986) recommends an annulus size of minimum 5 to 10 centimeters to ensure that an adequate sheath of grout is in place to form a proper seal. A smaller space may cause problems in transmitting the grout uniformly to the desired depth.

The optimal practice in sealing wells is to fill the entire annular space with grout through the use of either a *tremie* line or a pump through casing method (Driscoll , 1986). Grout is a non-permeable product designed for such purposes. It will not allow for the movement of water in the space around the outside of the casing. A more recent innovation is the use of grout chips, which can be poured down the outside of the well in order to fill the space with an impermeable material. This can greatly reduce the equipment required and cost of grouting, but requires a larger annulus and a great deal of patience to prevent the chips from bridging while being poured down the annulus.

Common practice in Ontario ranges from the use of the optimal practices, to the filling of the outside of the well casing with well cuttings (materials removed in the making of the well). The problem with this method is that these materials are not always impermeable and may in fact transmit water very well (Riewe, 1996). A second problem is that cuttings tend to bridge in the space between the casing and the well when being shoveled in; allowing for the creation of significant voids with absolutely no material at all in large portions of annular space.

The difficulty with employing the best practice of grouting the entire length of casing lies in the increased cost. Mixing grout to proper concentrations requires specialized equipment that is not present on many rigs. In addition to the expense of additional equipment, the added cost of grout can be very significant in increasing the overall cost of a well. Utilizing grouting chips can also be quite expensive. Perhaps the most reasonable compromise between the best practices described above and the common practice of using well cuttings would be to intersperse layers of well cuttings and grouting chips. This could be done utilizing techniques that prevent the bridging of materials, and would create an effective seal at a reasonable cost. The method could be employed both in drilled well or bored well situations.

It is of utmost importance that water well drillers are well informed of the need to properly seal the annulus of their wells. In many cases haste and undue care result in large voids within the annulus. Often grouting is not seen as a priority as it does not immediately affect the functioning of the well. Grouting is in fact a safety measure, and as is the case in many industries, safety measures are sometimes given low priority. This could impact the aquifer the well itself draws upon, or it could impact aquifers utilized by other wells in the surrounding area. The wells examined in Walkerton were often found to be improperly sealed.

4.2.4 Other Construction Concerns

There are a number of other areas where proper construction techniques are required to prevent possible contamination of wells. These include the sealing of the pitless adapters, the proper design of well pits, the chlorination of the well after completion, and the landscaping of the top of the well so that water flows away from it. Ontario's regulations generally follow best practices on these issues, so the remaining concern is ensuring that regulations are followed.

Common practices range from contractors who are very conscientious of the best practices around these issues to those who use a number of inappropriate shortcuts in the process. In most cases there is little expense to undertaking these measures and little reason not to utilize best practices.

4.3 Well Maintenance

Once a well is constructed, the consideration of well maintenance becomes important. Water well maintenance is necessary to prevent deterioration of the well that can lead to reduced performance and may increase the potential for contamination.

Numerous publications have been developed for owners of private wells that assist with proper maintenance and care. Examples of these are the Best Management Practices for Water Wells publication (AAFC-OMAFRA, 1997) and the 'Green Facts' publications put out by the MOE. For private well owners, recommended maintenance procedures typically involve annual to semi-annual testing of water quality, visual inspection of the well for leaks or cracks, and periodic shock chlorination treatments. This should be complemented by an inspection of the area around the well to ensure that the ground is sloped away from the well and that there are no depressions. This is a concern as the well annulus and the trench for a water pipeline can settle over time creating depressions that can promote surface water infiltration near the well. There are no regulations in Ontario regarding the maintenance of private water wells. This is similar in most jurisdictions in North America.

Further work needs to be done in promoting water well maintenance. The onus is left to well owners to seek out information on their own. Greater onus should be placed upon water well contractors to provide well owners with maintenance information (even if it is simply the provision of one of the available pamphlets) when working on either a new well or an existing well. Water well maintenance is in fact an area where water well contractors could expand their business. The institution of maintenance checks and regular maintenance of wells would be beneficial to contractors, well owners and other users that tap into the same aquifer. Such a program could be encouraged by provincial water well inspectors or the Ontario Ground Water Association.

Maintenance of municipal water wells is under legislated in Ontario. Regulations in Ontario are based upon the sampling of water supplies and a response being undertaken following contamination. This is a reactive measure to water well problems. A more proactive approach would involve regular water well inspection and maintenance involving hydraulic testing, water sampling, and visual inspections (including the use of borehole cameras to detect deterioration and leakages). Treatment would involve the use of chemicals and physical rehabilitation to prevent biofouling and well deterioration. Such a program would work to prevent the occurrence of well contamination *before* it occurs. While it may be argued that such an effort would be costly, it has been demonstrated that the costs of regular well maintenance are highly economical as they result in longer lasting and more productive wells (Smith, 1990). It is also much more economical than repairing wells or replacing them due to deterioration and a reduction in well yields. Just as regulations need to be put in place for proper maintenance of treatment plants, regulations need to be put in place for proper maintenance of water wells.

5.0 ABANDONED WELLS

The Ontario Groundwater Association has estimated that there are more than 100 000 abandoned wells across Ontario. There were 19 municipal or test wells abandoned in the Walkerton area that have since been located and properly retired. Water wells generally have a useful lifespan of less than 50 years (although there are exceptions), so it is reasonable to assume that any location that has been settled for more than 50 years may have old and unused water wells present. Abandoned wells tend to be the ‘old wells’ on the property. They are wells generally constructed greater than 30 years ago, with many being over 100 years old. Nearly all of these wells have been constructed improperly and have a high potential for contamination.

Improperly retired wells are of great concern because they offer a very large ‘contaminant shortcut’. They allow water to enter directly into aquifers with limited interaction with soil and rock that could filter some of the contaminants from the migrating water. The implications of this were discussed in earlier sections of this paper. (There are similar implications from abandoned gas and oil wells, but this paper will not go into detail on this topic). Unfortunately, in the past, wells were often located in the most convenient location. This usually meant very close to the barn or the house, which is often not the most desirable location today.

The Ministry used to have a team of well inspectors who received complaints directly and had the job of enforcing the well-plugging requirements. Over the past decade the unit has been reduced to only one inspector. Efforts have been made through programs such as the Environmental Farm Plan and the Best Management Practices series to educate farmers and other rural residents about the importance of the proper abandonment of these wells. The proper abandonment of a well ensures that it is no longer a contaminant pathway that could threaten the safety of the aquifer.

Wells should be retired in consultation with a licensed well driller to ensure the proper volume and types of materials and techniques are used. The methodology of well abandonment primarily focuses upon preventing the vertical movement of water. This can be achieved through filling the well with a non-permeable material. Commercial grouting products designed for this purpose are the most suitable. Recommended products include Neat cement grout, sand cement grout, bentonite chips, or bentonite grout The use of bentonite grout chips is an effective and efficient method for well owners to properly abandon their wells. This method is the most convenient abandonment method and avoids many of the potential difficulties encountered in using mixed grouting products. Impermeable, non-cracking materials should be the only products used in abandoning a well. The Water Wells Best Management Practices Booklet and other Ministry information sheets document some information on abandoning wells, however the discussion is very brief and in some cases does not reflect industry standards, or interpretation of the material may require practical experience for a meaningful interpretation.

A clear step-by-step guide for well abandonment should be developed and made available. Efforts should also be taken to inform the public of the importance of abandoning these wells. Abandoned wells that have not been plugged are a very serious environmental issue. There has to be a major program put in place to locate the wells and retire them properly. This will require government funding.

The Ontario Federation of Agriculture (OFA) has applied for funding from the "Healthy Futures for Ontario Agriculture" for two related projects. OFA is proposing the decommissioning of 5,000 rural water wells over the next two years, if the project is approved. In this project, the well owner will be responsible for the 35% of the decommissioning costs. It is estimated that the average decommissioning cost for each well will be $750, making the owner responsible for paying approximately $262.50 per well. The second project proposed is to complete well upgrades on 5,000 existing water wells to reduce the risk of contamination of the aquifer. Again, the well owner will be responsible for 35% of the cost to upgrade the well, along with 35% of the cost to test the well water. OFA is awaiting approval for these two projects.

6.0 AGRICULTURE'S ROLE IN WELLHEAD PROTECTION

Farmers represent only 15% of the rural population, but they own and manage a much higher percentage of the rural landscape. They rely on the air, soil and water to conduct their business, and as such, have a vested interest in the sustainability of these resources. Because of the nature of agriculture in Ontario, and the fact that farmers interact intimately with the natural environment on a daily basis, an agricultural perspective to water resources management is important.

The agricultural community in Ontario is aware of its environmental stewardship role, and has made significant management changes in the past ten years that reflect this consciousness. That is not to say, however, that there is not room for further improvements. Indeed, Ontario farmers are committed to continuous improvement on their farm operations.

There has been a growing concern regarding the impact of commonly accepted farming practices on the environment and the potential of off-farm resources becoming degraded. The agricultural community has been integral in supporting research to make Ontario's farms the most efficient and environmentally sustainable in North America, and perhaps the world. Our farming organizations have been very pro-active in their response to this dilemma, as well as tailoring current standards to incorporate new findings. In general, agriculture in Ontario aims to manage nutrients and pesticides efficiently to meet the needs of the crop, to reduce erosion and off-site migration of soil and nutrients, and to make efficient use of organic material, which is vital to the health of our soil. Nutrient management planning exercises are being promoted to ensure nutrient requirements are understood and addressed. Pesticide management has been addressed through the development of a mandatory Grower Pesticide Safety Course.

Many Best Management Practices have been developed to minimize the mobilization of nutrients, primarily nitrogen and phosphorous, to watercourses. In many cases, strategies implemented to keep excess nutrients from entering waterways are also effective in reducing transport of pathogens. However, in some instances, the best course of action to reduce nutrient mobilization may not have the same effect on pathogen migration. A recommended BMP is to use low-or no-till methods to reduce soil erosion and degradation. This minimizes migration of phosphorous which may impact nearby surface waters (lakes, streams, creeks, etc.). Research has also shown that these tillage practices increase the number and the persistence of macropores in the soil, which may provide potential pathways for contaminants to enter aquifers or groundwater (Ehlers, 1975; Edwards *et al.*, 1988; Edwards *et al.*, 1983; Goss *et al.*, 1993). A study by Conboy and Goss (2000) found that tillage practice did not predict vulnerability of Ontario wells. This may have been due to siting of the wells in domestic or barn areas that may have provided local influences. There is a need for research to provide farmers with up-to-date information regarding nutrient and pathogen transport, to ensure that their practices minimize the risk of contamination to the environment.

BMPs continue to be developed. Currently, the Ontario Cattlemen's Association is leading the development of a BMP booklet for Buffer Strips on Farms. This will include information on livestock access to waterways, to combat the concern that stream banks could become a bacterial reservoir when cattle are permitted to graze directly in adjacent streams, as observed by Kunkle (1970).

Another farming practice that has come under scrutiny recently is manure spreading. To address the concerns of manure spreading, OMAFRA has developed Best Management Practices (BMPs) for Manure Management, which provides guidance regarding the judicious use of manure. The BMPs recommend against spreading manure daily or on frozen ground. (AAFC-OMAFRA, 1994) Reducing the frequency of manure spreading and following current recommended practices may reduce contamination entering drinking water. This is supported by study findings. Conboy and Goss (2000) surveyed over 300 wells across Ontario. They found that the presence of livestock alone did not result in a well being vulnerable to contamination. Rather, they found an increase in well vulnerability on farms that spread manure more often than the typical spring and fall applications. Wells on farms spreading manure daily were especially vulnerable. Contamination was also inversely correlated with distance from feedlots or exercise yards (Goss *et al.*, 1998).

Another example of the complexities faced by farmers occurs with manure spreading. The agricultural community has adopted incorporation of manure into the ground as a 'good neighbour policy' as a means of controlling odour. One method of achieving this is to inject the manure directly into the ground. However, there are now findings that illustrate advantages to manure being left on the soil surface, from desiccation (drying) and ultraviolet rays from the sun may kill some forms of pathogens. This clearly indicates the need for continued research that will take a holistic approach to potential environmental impacts of agricultural practices.

The agricultural community, led by the Ontario Farm Environmental Coalition (OFEC), has actively sought to advance the responsible and appropriate application of nutrients by requesting legislation on nutrient management from the Provincial government. OFEC is recommending that the legislation require all farmers in the province to develop and implement a nutrient management plan tailored to their farm operation. These plans will be phased in over time and are site specific, to ensure the practices of each individual farmer are appropriate for the nature and location of his or her operation. This is preferable to having a single set, definitive standard that may not adequately address contamination concerns in some locations, while imposing excessive land use controls on others. For example, a restriction on spreading manure within X meters of a wellhead may be inadequate on one site, but excessively protective on another, depending on the hydrogeological factors on site.

Ontario's agricultural community demonstrated a proactive approach to the Province's resources, including water, long before the Walkerton tragedy occurred, through the development and promotion of the Environmental Farm Plan and several Best Management Practices documents. Several BMPs address water issues on farm, while many others address them indirectly. The agricultural community has also applied for "Healthy Futures for Ontario Agriculture" funding for two pilot projects to plug unused water wells and upgrade existing wells, as discussed above.

7.0 RECOMMENDATIONS FOR SAFER WELLS

Below is a list of OFEC's recommendations for safer wells:

i) **Use a multiple barrier approach. This includes, but is not limited to, appropriate siting, construction, maintenance, monitoring and treatment, and retiring abandoned wells.**

Siting: This requires an understanding of groundwater flow patterns and locations of potential contaminants to choose an appropriate site for locating a new well.

Construction: Construction involves using the appropriate type of well for the site, and ensures that construction standards are met. This includes the use of an appropriate casing, adequate grouting, and landscaping of the well.

Maintenance, Monitoring and Treatment: Both private and municipal wells require regular monitoring and maintenance. Well owners must be informed of the steps they can take to maintain their wells, and the frequency of these maintenance checks. This includes frequent, regular water testing. Records should be kept to monitor any changes over time. There are many resources available, such as some of the Best Management Practices booklets on water well maintenance. It may be as simple as having the well drillers provide these resources to well owners. In addition, municipal facilities must ensure that staff are appropriately trained to assess and understand the significance of indicators monitored. Staff must also be trained to adequately understand the treatment systems they are running and assess if it is the appropriate treatment for the monitoring and maintenance checks.

Locate and retire abandoned wells: There are a significant number of abandoned water wells across the Province, whose locations are unknown. Retiring abandoned wells requires educational programs so people understand their significance as a potential contaminant pathway. Incentives should also be offered to ensure as many wells as possible are retired. OFA's proposed project for decommissioning abandoned wells, if approved, will provide a good start to this initiative.

ii) **Use of Nutrient Management Plans as opposed to restrictive zoning**. There are several approaches to zoning. These include restrictive zoning that is focused on a water supply area as a special planning area. Another approach is performance zoning that set out the level of performance required for all land use activities. It is used to limit pollution loadings placing the onus of achieving the standards on the land user. Yet another approach is land use zoning that identifies permitted land uses on aquifers prohibiting those that could result in the contamination of the aquifer. This later approach does not allow for innovative practice and management that can mitigate potential adverse impacts.

Restrictive zoning practices can often have the same effect as expropriation without compensation. It is OFEC's position that site-specific, scientifically based reviews, and implementation of appropriate management practices are preferable to restrictive zoning practices that may be arbitrarily assessed. The nutrient management plan will take into account important environmental factors such as well capture zones and geography around a well to ensure its protection. Implementation of a nutrient management plan along with the application of best management practices, when coupled with an appropriate multiple barrier approach, can go a long way in protecting the environment, and well capture zones in particular. .

iii) **Programs such as the Environmental Farm Plan program, which reaches many individuals and initiates action to improving farming operations, must be continued.** There is a desperate need to increase the amount of funding available to ensure that programs like this, and research into agricultural and environmental issues continues over the long term.

iv) **Education and continued research are key components to protecting the water supply**. It must be applied to all people. For example, well drillers must be cognizant of the implications of siting and construction of wells, including casing, grouting and landscaping. Well owners/operators must be made aware of how to monitor their water and well, and of appropriate maintenance and treatment options. Farmers are also important players who must be educated on how to minimize their impact on the environment, and what management practices they can adopt to reach this goal. Much of this work requires continued research to ensure that the most current information is available and being adopted.

8.0 CONCLUDING REMARKS

Contaminant transport, including bacteria, into groundwater clearly cannot be easily predicted from soil type and geology alone. A number of factors must be considered for proper well placement. Different well constructions have different factors that affect vulnerability. There does appear to be some soil types and geological settings that are more vulnerable to contamination, but it also appears as though the condition of the well, location of contaminants and management practices in close proximity to the well capture zone must also be considered important in improving well water quality.

Any policy that looks to improve the safety of groundwater resources in Ontario must place heavy consideration upon the way in which water wells are constructed. Ontario should review its regulations and ensure that the standards are both of good quality and applicable in the industry. Such a review should involve members of the water well industry, with significant representation of some of the smaller operations in the province. Regulations must be both practical and effective. Secondly, there should be a concerted effort to build the professional base of the Ontario industry. Water well associations, such as those in Alberta and Montana, may offer models for building the strength of the Ontario organization. Greater interaction is required between the various individuals and groups in the industry, particularly with the agricultural groups and OMAFRA, who have done a great deal of good work on public water well education, and the water well industry. A publication aimed at water well contractors that details the contaminant risks and movement would be invaluable in assisting Ontario's water well contractors in upgrading their knowledge and skills around those particular subjects. The design of such a manual should be done in an accessible format, such as the *best management practices* publications for agriculture. Ontario has an invaluable groundwater resource; the costs of protecting it are minimal relative to the enormous return. Small efforts made now will pay dividends for generations.

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