EXAMINING SEEPAGE FROM EARTHEN MANURE STORAGE FACILITIES LOCATED IN SOUTHERN MANITOBA

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ABSTRACT
Continuous sample cores were collected from the base of ten earthen manure storage (EMS) facilities in located in typical hydrogeological settings in Manitoba, in order to assess the vertical migration of select chemical species from the facilities. The facilities examined ranged in operational age from three to twenty-nine years. Some of the facilities were in active operation and others had been abandoned at the time of sampling. Sample cores were sectioned into sub-samples and analysed in the laboratory for select chemical species known to be elevated in the stored wastewater. Elevated chloride concentrations were detected to depths of over 5 m. Ammonium was generally contained in the upper 2 m of the soil profile indicating that the underlying soils have a significant capacity to sorb ammonium. No phosphate migration was detected beneath the facilities. No nitrate migration and/or production was detected in the subsurface due to anaerobic conditions below the each of the facilities examined. Comparison of observed and predicted vertical chloride seepage profiles indicated average linear velocities in the underlying clay and till soil ranging from 0.05 m/year to 0.27 m/year and longitudinal dispersivity ranging from 0.01 m to 0.1 m. Coefficients of molecular diffusion were found to range from 0.003 m^2/year to 0.03 m^2/year. Parameter estimates were used to validate and/or select input parameter used for predictive two-dimensional advection dispersion modeling. Two predictive modeling scenarios were examined. Case I examined an unlined facility and Case II examined a clay-lined facility in the same hydrogeological setting. The results show that for non-fractured liner and subsoil scenarios, the presence of the liner causes a significant delay in the breakthrough of chloride into the underlying aquifer, even where the facility is underlain by native soils of relatively low permeability.

RÉSUMÉ
Examen des écoulements provenant de sites d’entreposage d’engrais situés dans le sud du Manitoba.

1. INTRODUCTION

The removal of grain transport subsidies, together with an increased demand for pork has resulted in dramatic growth of the intensive hog production industry in recent years throughout the Prairie Provinces of Canada. The majority of these operations use liquid manure systems and the resulting wastewater is often stored in large pits excavated into the native soils until applied to crop or rangeland as a soil amendment. The stored wastewater typically contains high concentrations of organic and inorganic constituents (primarily salts and nutrients) that have the potential to negatively impact groundwater quality should migration of these constituents from the facilities occur. This potential for impact to underlying groundwater supplies has been the impetus for a number of studies in the Prairie Provinces examining the subsurface migration of select chemical species from earthen manure storage (EMS) facilities over recent years.

In this study, a total of ten EMS facilities, located in southern Manitoba, were examined over a four-year period to assess the migration of select inorganic chemical species from the facilities into the subsurface. The work included the collection of continuous soil samples from the base of each of the facilities to depths of up to 7 m, and the chemical analysis of sub-samples to examine impacts. The facilities studied ranged in operational age from three to twenty-nine years. Some of the facilities were in active operation at the time of sampling and others had been abandoned. All of the facilities examined are located in typical hydrogeological settings encountered in agro-Manitoba.

The examination of soil quality profiles, together with estimates of parameters effecting the movement of chemical species into underlying aquifers, allow for an assessment of the performance of existing EMS facilities. The predictive modeling component of this work provides valuable insight into the performance of hypothetical or existing facilities under various scenarios which may be encountered.

In this paper, the analytical results of one soil sampling event for a single EMS facility examined are highlighted. The parameter estimation and/or validation process is discussed and the results shown graphically for the same facility. Using the deduced parameter estimates, prediction of chloride migration from two different hypothetical EMS construction scenarios is examined.

2. GEOLOGY AND HYDROGEOLOGY

Glaciolacustrine clay and/or till deposits, from 7 m to over 50 m in total thickness, overlie bedrock at the sites examined. The deposits are the result of Wisconsinan glaciation and associated episodes of glacial Lake Agassiz (Teller and Fenton, 1980). These overburden materials can be extensively fractured, particularly in the upper weathered zone (Grisak and Cherry, 1974; Pach, 1994).

Six of the ten sites examined are underlain by highly fractured and paleokarstic carbonate bedrock aquifers, typically associated with the upper portion of the Ordovician Red River Formation bedrock (Render, 1970; Betcher et al., 1995). Each of these six sites obtains groundwater for livestock and/or domestic purposes from the underlying aquifer. One of the sites examined is underlain by Precambrian bedrock which is adequately fractured in the upper portion to provide a sufficient quantity of water to meet the needs of the operation and residence located on site (GWDrill Database; Betcher et al., 1995). The remaining sites use localized sand and gravel overburden aquifers as a source of water to meet the domestic and operational needs of the facilities and/or local residents (GWDrill Database).

A significant portion of the recharge to local surficial aquifers at the sites examined is from downward flow as infiltration through the clay and/or till overburden (Betcher et al., 1995). The water table is typically shallow, varying from ground surface to depths of approximately 3 m below grade. Horizontal gradients have been estimated for the carbonate bedrock aquifers and are typically on the order of 0.001 (Betcher, 1986; Kennedy, 2002). Falling head tests, conducted as part of this work, and yielded bulk hydraulic conductivity estimates for the clays and tills of 10^{-6} m/s to 10^{-9} m/s.

3. METHODOLOGY

3.1 Soil Sampling and Analysis

A total of fourteen continuous sample cores were collected from the base of the ten EMS facilities examined. At all of the sites, one sample core was removed from the base of the facility. At three of the sites an additional sample core was collected in a subsequent year, to examine temporal changes in the profiles. At one site, an additional sample core was collected at the same time as the initial sample core, but in a different location, to address the potential for spatial variability in chemical species distributions beneath the base of the facilities.

Each sample core was sectioned into discrete sub-samples and analysed in the laboratory for a number of inorganic chemical species including chloride, potassium, sulphate, ammonia and/or ammonium, nitrate+nitrite and/or nitrate and phosphate using either a saturated paste analysis method or a 2:1 dilution method. Sub-samples were also analysed in the laboratory for gravimetric moisture content.

3.2 Performance Assessment and Parameter Estimation and/or Validation

Soil quality profiles were constructed for each of the sites to evaluate the extent of vertical inorganic species migration from the facilities. Soil quality profiles were constructed by plotting species concentrations in mg/kg versus the average depth of the sub-sample. The soil quality profiles were examined to evaluate the performance of each of the facilities.

Chloride concentrations on a mg/kg basis were converted to pore water chloride concentrations in mg/L using the moisture contents measured for each sub-sample. The resulting observed chloride migration profiles were then compared to predicted chloride migration profiles for each of the fourteen EMS sample cores collected. Predicted chloride migration profiles were developed using the Ogata-Banks (1961) solution to the one-dimensional advection dispersion equation. Average linear groundwater velocity, longitudinal dispersion and molecular diffusion were varied within predefined ranges which were based on literature published values until the RMS error between the predicted and observed profile was minimised.

The Ogata-Banks (1961) solution is considered valid for a fully saturated homogeneous porous medium of semi-infinite vertical extent. Typically, a one-dimensional solution is considered valid for cases where the source footprint is large, horizontal gradients in the overburden are sufficiently small, and overburden thicknesses are large. These assumptions are generally considered valid for the majority of the sites examined in this work.

It should be noted that the concentrations of chemical species within the stored liquids contained in the EMS facilities, as well as depth of manure ponding fluctuates seasonally and with operational stages. These variations in source concentrations and loading are not considered in the Ogata-Banks (1961) solution and may account in part, for variability in chemical species concentrations observed within the upper portion of the soil profile (e.g. Figure 1). For the times examined in this work, the use of a constant input concentration representing the average concentration within the lagoon was considered a reasonable approximation.

3.3 Predictive Modeling

The resulting parameter estimates can be used to predict impact on the underlying aquifers. The predictions can be made for various hydrogeological settings, facility configurations, and source loading conditions that are typically encountered, using a two-dimensional finite-layer solute transport model (MIGRATEv9). MIGRATEv9 provides a semi-analytical solution to the two-dimensional advection dispersion equation, and allows for variable velocities between strata (Rowe et al., 1995).

Two predictive modeling cases, Case I and Case II, are examined. Both cases examine the impact of a hypothetical EMS facility on the underlying soils and aquifer. In Case I, a facility overlying 7 m of till followed by a 3 m thick aquifer is simulated. Case I simulates a facility constructed with no recompacted clay liner. In Case II, a facility of the same dimensions and situated in the same hydrogeological setting is simulated, however this facility has been constructed with a 1 m thick recompacted clay liner overlying 6 m of till. An input chloride concentration of 1000 mg/L was used to represent the source concentration, and was selected based on typical values observed as part of this work.

For both the Case I and Case II simulations, the underling aquifer was assumed to have an average horizontal groundwater velocity of 10 m/year (e.g. Kennedy, 2002), on the downgradient side of the facility, and a coefficient of hydrodynamic dispersion in the longitudinal direction of 1 m^2/year (Gelhar et al., 1992). Additional parameters used to simulate overburden material(s) in the generic modeling component are discussed in Section 4.1.

4. RESULTS AND DISCUSSION

4.1 Performance Assessment and Parameter Estimation

Figure 1 shows a soil quality profiles constructed based on the results of a single soil sampling event beneath an active EMS facility. The sampling was conducted seven years after facility operation commenced. The site is located in the Interlake area of Manitoba and the surrounding area is characterized as gentle to no topographical relief (Betcher et al., 1995). Approximately 32 m of till separates the base of the EMS facility from the underlying bedrock. The underlying carbonate bedrock has significant water-bearing capacity in the upper fractured zone and is used as a potable water supply in the surrounding area (Betcher et al., 1995; GWDrill Database).

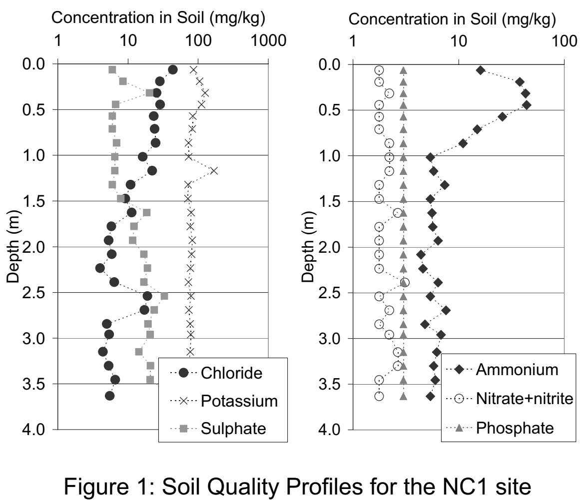

Figure 1: Soil Quality Profiles for the NC1 site

The soil quality profile shown in Figure 1 suggest that after seven years of facility operation, chloride originating from the EMS facility has migrated to a depth of approximately 2 m below grade and ammonium has migrated to a depth of approximately 1 m below grade. No phosphate or nitrate migration or nitrate production is evident in the underlying soil profile. No distinct trends are evident in either the potassium or sulphate profiles.

In general, each of the ten EMS facilities examined showed evidence of the vertical migration of chemical species, originating from the facilities, through the underling soil. Elevated chloride concentrations were observed beneath all of the EMS facilities examined and occurred to the greater depths than the other chemical species examined, particularly at facilities which had been operating the longest. This result was expected due to the conservative nature of chloride in the subsurface (Domenico and Schwartz, 1998). Elevated ammonium concentrations were also noted beneath each of the ten facilities examined. At each of the facilities, elevated ammonium concentrations were limited to the upper 2 m of the underlying soil profile, indicating that ammonium movement is limited and that the underlying soils have significant capacity for the sorption of ammonium. No vertical migration of phosphate or nitrate or production of nitrate was observed beneath the any of the facilities examined. The lack of nitrate production is likely the result of anaerobic conditions within stored liquids and in the soils underlying the facilities, which prevent the nitrification of the available ammonium to nitrite and nitrate.

Using the parameter estimation technique discussed in Section 3.2, average linear groundwater velocities, longitudinal dispersion and coefficients of molecular diffusion were estimated for the geological materials examined. Figure 2 shows the predicted and observed chloride seepage profiles for the same sample core shown in Figure 1, collected seven years after facility operation commenced. For this example, average linear groundwater velocity was estimated to be 0.10 m/year, longitudinal dispersivity was estimated to be 0.1 m and molecular diffusion was estimated to be 0.03 m^2/year.

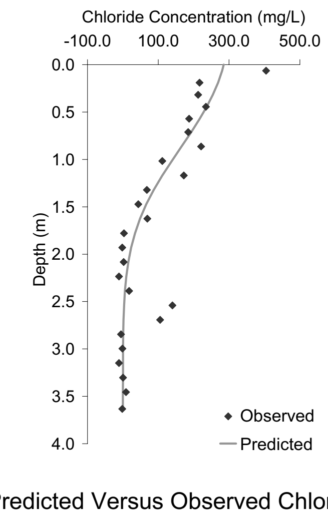

Figure 2: Predicted Versus Observed Chloride Seepage Profile for the NC1 Sample Core

Average linear groundwater velocities were found to range from 0.05 m/year to 0.10 m/year in the underlying clays and 0.10 m/year to 0.27 m/year in the underlying tills. Longitudinal dispersion was found to be on the order of 0.01 m to 0.04 m in the clay and 0.02 m to 0.1 m in the till. Coefficients of molecular diffusion were estimated to range from 0.003 m^2/year to 0.03 m^2/year.

Estimates of Darcy velocity in the vertical direction (q_v) and longitudinal dispersion (D_L) as approximated and/or validated with the parameter estimation technique were used to represent the till and/or clay materials underlying the hypothetical EMS facility presented in Case I and Case II. These parameters, along with estimates of effective porosity (n_e), used in the predictive modeling scenarios are provided in Table 1. For each case examined, transverse dispersion was estimated to be 10% of the longitudinal dispersion.

Table 1: Parameter Values Used in Generic Predictive Modeling Case I and Case II

Scenario	***Material***	***q_v (m/year)***	***n_e***	***D_L (m^2/year)***
Case I	Till	0.03	0.2	0.03
Case II	Clay (Liner)	0.007	0.4	0.003
	Till	0.007	0.2	0.03

It should be noted that in Case II, Darcy velocity in the vertical direction is calculated using an effective hydraulic conductivity for flow perpendicular to stratification (e.g. Freeze and Cherry, 1979) and the hydraulic gradient used in Case I is maintained for Case II. This allows for a direct comparison between the two cases.

4.2 Generic Predictive Modeling

Figure 3 shows a comparison of the vertical migration of chloride beneath the centre of a hypothetical EMS facility for Case I and Case II at times of 5 years, 15 years, 25 years and 50 years after facility operation has commenced.

The results presented in Figure 3 suggest that the installation of the clay liner (examined in Case II) causes a significant delay in the breakthrough (first instance of impact) of chloride into underlying aquifer beneath the centre of the facility, compared to the unlined facility (Case I). The delay in breakthrough due to the presence of the clay liner is on the order of 80% after 5 years and 15 years and on the order of 75% after 25 years. This would suggest that the effect of the liner is significant during the typical operational lifespan of an EMS facility (on the order of 25 years).

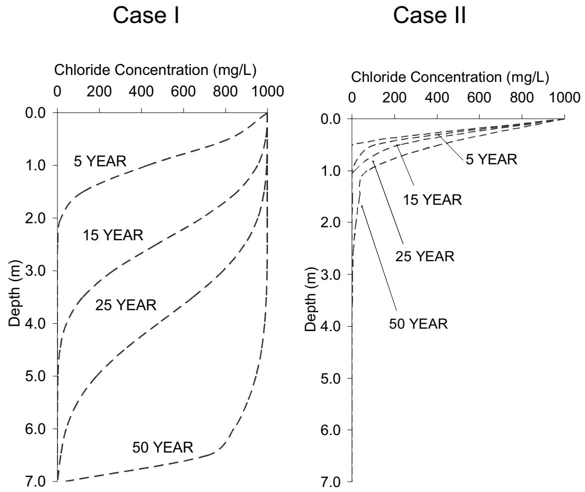

Figure 3: Predicted Vertical Chloride Migration for Case I and Case II

Figure 4 shows chloride concentrations with distance from the centre of the facility, within the underlying aquifer, at 30 years, 40 years, 50 years and 100 years after facility operation commenced.

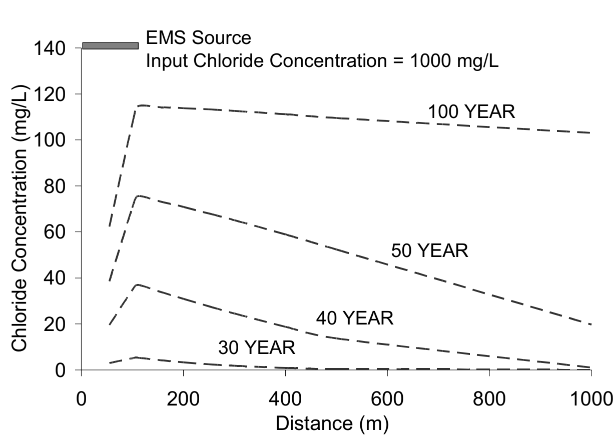

Figure 4: Predicted Chloride Impacts in the Underlying Aquifer for Case I

For Case I, impacts are first detected in the underlying aquifer between 25 years and 30 years after facility operation has commenced. Under the assumption of continued constant source loading, concentrations continue to increase with time within the aquifer. For Case II, no impacts are detected in the aquifer at times of 100 years or less after facility operation has commenced.

Based on the results of the predictive modeling presented in Case I and Case II, the installation of a clay liner will cause a significant delay in the breakthrough of conservative chemical species into the underlying aquifer. In Case I, breakthrough to the underlying aquifer occurs between 25 years and 30 years after facility operation has commenced, while in Case II breakthrough of chloride into the underlying aquifer occurs 200 years after facility operation has commenced (assuming constant and continued source loading over the entire time period). As a result, the decrease in the time of breakthrough due to the presence of the clay liner is on the order of 85%.

5. SUMMARY AND CONCLUSIONS

Continuous sample cores were collected to depths of up to 7 m beneath ten EMS facilities located in typical hydrogeological settings in agro-Manitoba. The sample cores were sectioned into discrete sub-samples and analysed in the laboratory for chloride, potassium, sulphate, ammonia/ammonium, nitrate+nitrite and/or nitrate concentration. Each of these chemical species is typically elevated in the liquids stored in the facilities.

Chloride migration occurred to the greatest depths beneath the facilities examined, followed by ammonia and/or ammonium which was generally contained within the upper 2 m of the soil profile as a result of sorption to the underlying soils. No evidence of phosphate migration or nitrate+nitrite/nitrate migration and/or production was observed. The lack of nitrate productions is considered to be a result of anaerobic conditions within the stored liquids and the soils underlying the facility while the facility is operational. Should the facility be abandoned in such a manner as to allow aerobic conditions to develop in the ammonium-rich sub-soils underlying the facility, significant production of nitrate is possible.

Based on a comparison of observed chloride seepage profiles developed for each of the facilities and predicted chloride seepage profiles developed using the Ogata-Banks (1961) solution to the one-dimensional advection dispersion equation, average linear groundwater velocities in the underlying soils were estimated to range from 0.05 m/year to 0.10 m/year in the clay and 0.10 m/year to 0.27 m/year in the till. Longitudinal dispersion was estimated to range from 0.01 m to 0.04 m in the clay and 0.02 m to 0.1 m in the till, and coefficients of molecular diffusion were estimated to be on the order of 0.003 m^2/year to 0.03 m^2/year.

Predictive modeling of a hypothetical EMS facility was conducted under two construction scenarios (Case I and Case II). In Case I, the facility was underlain by 7 m of till followed by a 3 m thick aquifer with an outflow velocity of 10 m/year and a longitudinal dispersion of 1 m^2/year. In Case II, the facility was simulated in the same setting, however a 1 m thick clay liner replaces the upper 1 m of the underlying till. The source concentration in the simulated facility was assumed to be constant at 1000 mg/L and continuous over the times simulated.

The results of the predictive modeling simulations suggest a significant delay in the breakthrough of elevated chloride concentrations into the underlying aquifer for the lined EMS facility case presented in Case II (breakthrough at 200 years compared to breakthrough at approximately 25 years to 30 years for Case I). This would suggest that the effect of the liner is significant during the typical operational lifespan of an EMS facility (on the order of 25 years), even where the facility are underlain by native soils of relatively low permeability.

It should be noted that the predictive modeling presented does not consider the potential for fracturing of liner materials due to wetting and drying cycles, erosion and/or wave action on inner berms, plant growth, etc. Although not examined in this paper, the presence of fractures both within the liner and within the underlying native soils may have a significant impact on the chemical species migration and breakthrough and have been considered in additional modeling simulation conducted as part of this work.

6. ACKNOWLEDGEMENTS

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