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Vadose Zone Monitoring of Dairy Green Water Lagoons using Soil Solution Samplers

James R. Brainard
Amy K. Coplen

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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James R. Brainard
Amy K. Coplen
Department XXXX
Sandia National Laboratories
Albuquerque, NM 87185-0782

Abstract

Over the last decade, dairy farms in New Mexico have become an important component to the economy of many rural ranching and farming communities. Dairy operations are water intensive and use groundwater that otherwise would be used for irrigation purposes. Most dairies reuse their process/green water three times and utilize lined lagoons for temporary storage of green water. Leakage of water from lagoons can pose a risk to groundwater quality. Groundwater resource protection infrastructures at dairies are regulated by the New Mexico Environment Department which currently relies on monitoring wells installed in the saturated zone for detecting leakage of waste water lagoon liners. Here we present a proposal to monitor the unsaturated zone beneath the lagoons with soil water solution samplers to provide early detection of leaking liners. Early detection of leaking liners along with rapid repair can minimize contamination of aquifers and reduce dairy liability for aquifer remediation. Additionally, acceptance of vadose zone monitoring as a NMED requirement over saturated zone monitoring would very likely significantly reduce dairy startup and expansion costs.

Acknowledgment

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Nomenclature

ΔP	Pressure differential across a meniscus
Cl	chloride
EMI	electromagnetic inductance
GWQB	Ground Water Quality Bureau
millibar	mb
NMED	New Mexico Environment Department
NO_3-N	nitrate-nitrogen
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
WQCC	Water Quality Control Commission
XBGPR	cross-borehole ground penetrating radar

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1. Introduction

New Mexico is the seventh largest dairy producing state in the nation. The counties contributing to this ranking are Chaves, Curry, Roosevelt, Doña Ana, Lea and Eddy (New Mexico Agricultural Department, 2002). The New Mexico Department of Labor reported that in 2002, New Mexico dairies employed over 3,000 people with an estimated payroll of $64.8 million dollars. This workforce produced 63 million gallons of milk from 310,000 cows. These factors make New Mexico dairies the largest income producers for the farmers and ranchers of New Mexico.

Along with the positive economic impact of dairy operations is the potential for negative environmental impacts. Of major concern is the impact on ground water quality from improper green water and manure management practices. Dairy cows drink between 25 and 50 gallons of water per day, depending on the weather, volume of milk production, weight of the cow, etc. Additional fresh water is used to wash the cows and the milking barn (including tanks, lines, etc.), and to flush the feed lanes.

Of the total amount of water pumped for dairy use, approximately 50% is discharged to lined lagoons. At most dairies, green water in the lagoons is combined with irrigation water to grow feed crops for the dairy cows, while in fewer instances the lagoon water is evaporated leaving behind a semi-solid manure slurry. The discharge of green water is regulated by the New Mexico Environment Department (NMED) Ground Water Quality Bureau (GWQB) through the Ground Water Discharge Permit process. This permitting process applies to all aspects of solid and liquid manure storage, treatment and disposal. Among other requirements, the permit stipulates lagoon construction specifications for containment of process and storm water and requires monitoring well installation to provide the means for evaluating the impacts of the dairy operation on groundwater quality and the necessary data to alter dairy operations if water quality standards are exceeded.

Usually three monitoring wells are required at dairy facilities, one located up gradient (hydrologic gradient) of the facility, one down gradient of the lagoons, and one down gradient of the land application area. Each of the ground water monitoring wells is required to be sampled prior to discharging, as well as on a quarterly basis thereafter. Prior to sampling, the depth to ground water is measured in order to confirm direction of the local gradient and therefore the direction of flow. The samples are analyzed for the concentrations of nitrate-nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), chloride (Cl), and total dissolved solids (TDS).

If New Mexico Water Quality Control Commission (WQCC) ground water quality standards are exceeded in a monitoring well, the operator must collect a confirmatory sample within 15 days. If the confirmatory sample analysis is consistent with the initial sample analysis, then the dairy operator must submit an abatement plan to the GWQB within 30 days of confirmed ground water contamination. The abatement plan requires a site investigation to define the source, nature and extent of contamination, as well as proposed corrective actions.

Leakage from failed green water lagoon liners, whether the liner is engineered clay or a synthetic liner with welded seams, can pose a significant risk to groundwater quality. Leaks in liners can go undetected until increased levels of contaminants are measured in water samples collected from monitoring wells. The question to ask here is whether or not reliance on monitoring wells to monitor the integrity of lagoon liners is the best approach to safeguard groundwater resources. A more logical approach is to monitor the vadose zone, and/or engineered back fill, beneath dairy lagoons.

The vadose zone (or unsaturated zone) is defined as the zone above the regional water table and includes local perched aquifers. In the dairy producing areas in New Mexico, depths to the regional water table can be upwards of 100 meters along basin margins and highlands surrounding the basins and less than 10 meters along rivers located in alluvial valleys within the basins. Early detection in thick vadose zones provides the opportunity to halt downward movement of contaminants before they reach depth beyond which they cannot be removed. While in thin vadose zones immediate detection is needed to prevent ground water contamination. Vadose zone monitoring offers the advantage of early detection of failed liners, and thus the opportunity to take fast action to prevent further spread of the contaminants.

Numerous vadose zone monitoring technologies have been commercially produced and successfully used in a variety of research and real world applications. These technologies range from point measurements using long-used technologies such as neutron logging, electromagnetic inductance logging, and various dielectric dependent methods; to newer tomographic imaging techniques where two and three-dimensional images are developed from radar and electrical resistance surveys. Each of these technologies has technical strengths and weakness which require consideration in choosing one measurement technique over another.

One of the major concerns of placing permanent sensors in the subsurface is the potential for long term signal degradation resulting in false readings. This is especially a concern with sensors that have metal in direct contact with the ground and the measurement result is dependent on an electromagnetic signal. Two such technologies are time and frequency domain reflectometry – dielectric based measurements- and electrical resistivity tomography. An alternative to placing sensors in the ground would be to install PVC casing horizontally underneath lagoons and take measurements from sensors dragged through the casing. The three technologies that could be automated and adapted to such a system include: 1) neutron logging where collision of fast neutrons emitted from the on-board neutron source are thermalized by hydrogen or protons within the formation/soil and reflected back to the on-board thermal neutron detector; 2) electromagnetic inductance (EMI) logging where a on-board transmitter coil produces secondary electromagnetic fields in the formation/soil surrounding the borehole which then produce voltages in the on-board receiver coil, the magnitude of which is dependent on the formation/soil electrical conductivity; and 3) cross-borehole ground penetrating radar (XBGPR) where tomographic maps are built from signal response to moisture content between adjacent tubes through which an transmitter and receiver are dragged. The XBGPR method is a dielectric based measurement where arrival times of radar frequency electromagnetic waves are used to build tomographic maps of the moisture content. For examples of vadose zone monitoring studies using EMI see Hall et al. (2004) and for XBGPR see Alumbaugh et al. (2002). A recent EPA report (EPA, 2004) gives a brief summary of some of the technologies mentioned above along with others not mentioned that have been implemented to monitor containment liners and covers at hazardous waste landfills and surface impoundments.

Numerous obstacles prevent the implementation of such advanced monitoring of the vadose zone at dairies including stringent requirements for storage of radioactive sources and the cost associated with design, construction, installation, and maintenance of automated systems, as well as costs associated with data analysis and verification.

Because of these limitations, we are forced to consider other technologies that are inexpensive and simple in design and operation, while still having the potential to identify lagoon liner failure. Of the commercially available technologies that meet these criteria, arrays of porous cup solution samplers installed either underneath clay or synthetic liners, or within clay liners hold promise to provide evidence for liner leakage. Solution samplers have been extensively used with good results in the agricultural arena for more than 50 years and in the "environmental conservation" field for the last 25 years. A survey of the research literature shows that solution samplers have been used with good success in numerous studies dealing with nutrient cycles in natural and agriculture soils and in contaminant transport studies. As with any of the devices that provide a point measurement, solution samplers must be installed in closely spaced grids to pinpoint leaks or the installation must target the most likely areas of leaks such as at the corners of lagoons where the liner may be subjected to tensional forces and therefore be especially prone to failure.

In this report we propose a study to evaluate solution samplers as a potential for partial or full replacement of down gradient monitoring wells at New Mexico's dairies. The three major issues to be addressed in the proposed study are: 1) the long term performance of solution samplers installed beneath dairy lagoons and 2) the appropriate type of solution sampler to be used for each liner type, and 3) the development of cost and technically effective installation procedures.

2. Solution Samplers

2.1 Background Information

The vadose zone (also commonly called the unsaturated zone) is comprised of soils and geologic materials above regional water tables and, except where localized lenses of perched water occur and at capillary fringes above perched and regional water tables, sediments are in an unsaturated state. As is the case in the saturated zone, potential energy gradients drive water movement in the vadose zone. Unlike the saturated zone, vadose zone water pressures are negative and the degree of saturation varies. Capillary physics plays an essential role in determining the degree of saturation in the vadose zone. Therefore pore dimensions, as well as the spatial distribution of pore sizes and the wetting and drying history all play a role in the moisture content distribution within the vadose zone. Capillary physics also impacts the movement of water in the vadose zone through the dependence of the hydraulic conductivity on saturation which creates a non-linear relationship between water flux and the potential gradient. These factors have a profound impact on water flow in the vadose zone and important implications for proper installation and operation of solution samplers. Below we give a brief overview of a common solution lysimeter design, operation theory, porous cup selection, and installation guidelines.

2.2 Solution samplers

Solution samplers are simple devices that operate according to fairly straightforward principles where water moves from the formation/soil through a porous cup in response to an applied vacuum in a sample collection chamber. A typical solution sampler consists of a two inch diameter by eighteen inch long pipe with a cap or a rubber stopper installed on one end and the porous cup on the other. Access for applying a vacuum and removing a water sample from a buried lysimeter is through two one-eighth or three-sixteenth inch diameter tubes installed through the capped end of the pipe, one of which extends to the end of the porous cup and the other to the bottom of the porous cup (Figure 1). After saturating the porous cup with water, solution samplers are typically installed in silica flower slurry in the bottom of the well. The silica flower assures that hydraulic connection is maintained between the water in the porous cup and that of the formation/soil. Following installation, a backfill of a bentonite mix is used to seal the well to prevent percolation of water down the well.

Sampling procedures involve clamping off the longer tube while using a vacuum pump to remove air from the lysimeter through the short tube. Once the desired vacuum has been reached, the tube is clamped off. In so doing, the vacuum within the lysimeter imparts a negative pressure to the water in the porous cup and then to the surrounding formation/soil. If the water pressure in the porous media is greater (less negative) than the air pressure in the lysimeter, the resulting hydraulic gradient will cause water to flow through the porous cup and drain into the lysimeter.

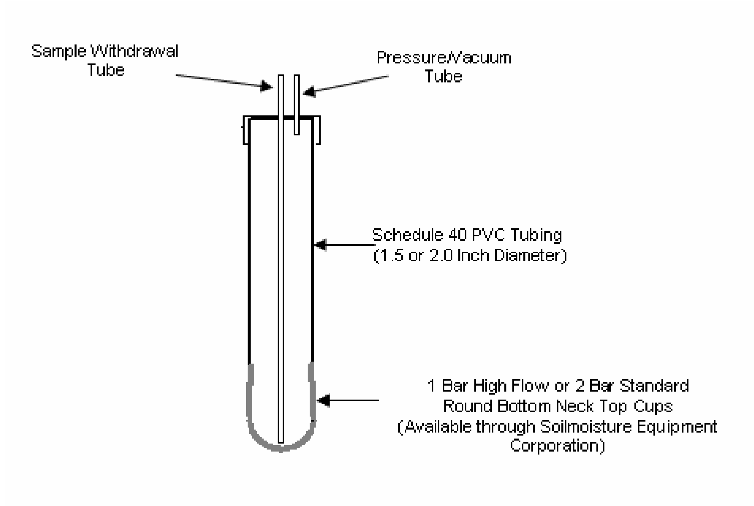

Figure 1. Schematic of solution sampler.

As such, the porous cup material is a critical aspect of solution sampler design: the cup must be hydrophilic, have numerous and appropriately sized pores to easily transmit water, be inert with respect to the constituents of the solution, and it must remain saturated during the sampling process.

If a pore channel within the porous cup desaturates (i.e., the air entry or bubbling pressure of the porous cup is exceeded) before surpassing the formation/soil water pressure, then water will not be drawn into the lysimeter. In fact, water will be drawn out of the porous cup until the water pressure in the cup reaches equilibrium with the soil water pressure. Therefore if dry formations are being sampled, the porous cup must be able to support a fairly large vacuum. The ability to do so is dependent on the capillary phenomena where both the pore-size distribution of the cup and the surface tension of the fluid play a role.

The capillary rise equation gives the relationship between the pressure difference of the gas and liquid pressure across a meniscus ΔP; the liquid surface tension (σ), the pore radius (R), and the contact angle between the fluid and the solid phases (γ):

$$\Delta P = \frac{2\sigma \cos\gamma}{R}$$

The air entry pressure is the pressure differential across a meniscus at which a pore of radius R can no longer support the meniscus. The capillary rise equation can also be written as

$$\Delta P = \frac{2\sigma}{r}$$

where r is the radius of curvature of the meniscus. See Figure 2 where these terms are described schematically and see Jury (1991) and other vadose zone texts which provide more detailed information on this topic.

$$\Delta P = \frac{2\sigma \cos \gamma}{R}.$$

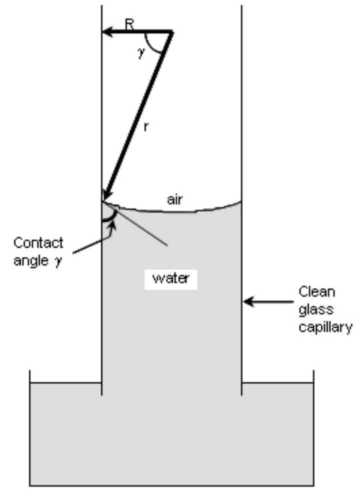

Figure 2. Schematic of capillary rise in a capillary tube illustrating the contact angle (the angle between the liquid-solid interface and the liquid-air interface) and the radius of the capillary tube.

These equations indicate that smaller pores can support smaller radiuses of curvatures than larger pores and therefore can support larger pressure differentials across the meniscus. In turn bubbling pressures are greater for materials with small pores. Porous cup materials must therefore have an average pore size with a narrow distribution suitable for the particular soil to be sampled. In contrast, porous cups must be relatively permeable so as to not constrict flow of water into the sampler. It follows that the selection of porous cup material is critical to correct operation of solution samplers.

Five materials are candidates for use as porous cups: porous plastic films; porous plastic shapes; sintered metals; stainless steel, and ceramics. Each of these materials, especially the first three have drawbacks which include the following:

- the plastic films are easily damaged;
- porous plastics have large non-uniform pores and are hydrophobic unless treated;
- sintered metals also have non-uniform pore sizes, have high ion exchange capacities, and can oxidize under certain conditions;
- stainless steel has non uniform pore sizes.

Non uniform pore sizes result in relatively low air entry values which limit the range of operation.

Ceramics have none of these drawbacks but cannot tolerate excessively rough handling. Despite this one drawback, ceramics have historically found application and long term use, with alumina porcelains being preferred for their inert and durable characteristics.

2.3 Relevant Research

Solution samplers have been used to detect NO_3-N and NH_4-N in pore water in numerous studies. One of the major concerns in using solution samplers is adsorption of anions (i.e., PO_4-P and (NO_3-N) and leaching of certain cations (i.e., Ca, Mg, and Al) from the ceramic porous cups. Because presence of NO_3-N in samples collected with solution samplers installed beneath the liners may indicate a leaky liner, studies involving interactions of other ions with the porous cups are not addressed here.

Peer reviewed journals contain numerous papers addressing both performance of field samplers and their application to field studies involving NO_3-N concentrations. Silkworth and Grigal (1981) compared four types of samplers, one of which was a fritted glass porous cup, and concluded that the large diameter (4.8 cm OD) ceramic cup samplers performed the best both in terms of minimum alteration of soil solution and a low failure rate. In a comparison study between samples with porous ceramic cups and porous Teflon, Zimmerman et al., (1978) reported that the ceramic sampler collected 11 % of the NH_4 from a test solution while the Teflon sampler collected near 100%. However Hansen and Harris (1975) and Wagner (1962) reported that NO_3-N was not adsorbed by the ceramic cups of soil solution samplers while Levin and Jackson (1977) and Nagpal (1982) found that the ceramic porous cup decreased the concentration of NO_3_NO by less that 5%. Other porous materials have also been comparatively investigated, including the materials mentioned in a previous section in this report, yet ceramic remains the most commonly used cup material. Wagner (1962) concluded that porous cups with large amounts of Al_2O_3 are the best for sampling soil pore water and Beier and Hansen (1992) suggested that the conflicting results obtained with ceramic porous cups results from variations in the compositions of the ceramic material.

As mentioned previously, ceramic cup solution samplers have been used successfully in field scale nutrient studies. Paramasivan et al. (2001) evaluated NO_3-N and N distributions for two cropping seasons under orange trees in central Florida, and Trudgill et al. (1991) derived average concentrations of NO_3-N in a 2-ha field in South Deven, UK.

The review given above shows that solution samplers have been evaluated in the peer reviewed literature for the ability to collect NO_3-N and that they have been deployed successfully in the field where NO_3-N concentration is one of the critical measures to the studies. Apparently no research involving application of solution samplers to the monitoring of dairy lagoon liners has been published in the peer reviewed literature. The lack of published papers on this topic does not indicate that dairy liners have not been successfully monitored with solution samplers; rather it suggests that little attention has been given to this area of vadose zone monitoring. Based on the above literature review, the successful implementation of a solution sampling program to monitor leakage from a dairy lagoon, such as that proposed in the next section may be reasonably expected. Additionally, the lack of published results on this topic suggests that results from an investigation of using solution samplers to monitor lagoon liners will be of value not only to dairy farmers here in New Mexico, but also throughout many other states in the U. S.

2.4 Dairy Lagoon Monitoring Proposal

A comprehensive and detailed plan to investigate the use of solution samplers for early detection of leaks from dairy lagoons at this point is not feasible as there are too many unknowns concerning both installation details and suction lysimeter performance. The primary concerns are: 1) whether or not water samples can be obtained from the solution samplers and 2) whether or not samplers can be installed in optimal locations beneath existing lagoons. The first concern arises from both the limitation of the solution sampler method and failed samplers due to damaged porous cups while the second arises from the awareness that full coverage underneath a lagoon with an array of solution samplers is not possible and the uncertainty involved in choosing optimal locations where leakage is most likely to occur and then being able to install the solution sampler at optimal locations.

The practical limit for water flow in soils is between 650 and 850 mb (millibar) of water tension. Non-agricultural soils and porous vadose zone deposits in the arid southwestern United States commonly have tensions well above these limits as well as tensions easily exceeding the bubbling pressure of commercially available ceramic porous cups (approximately 2 bars). Determining if the bubbling pressure has been exceeded when a sample is not obtained can be somewhat problematic. If samples cannot be collected and yet the porous cup maintains saturation, the lack of a sample could suggest an intact liner. However, a procedure would have to be developed to verify the saturation state of the porous cup. If the cup is desaturated, the procedure would have to include a process to resaturate the porous cup while wetting the surrounding soil to decrease the soil water tension. The rate of decline of vacuum within the solution sampler following an attempted sampling event may indicate the saturation status of the porous cup. The falloff in pressure could be monitored with a pressure transducer connected to one of the sampling tubes and monitored with a datalogger.

Damaged porous cups could also prevent sample collection. Solution samplers need to be tested before installation. The likelihood of damaging the ceramic porous cups between testing and installation of the solution sampler can be greatly minimized through sensible handling. The cups are not extremely fragile, but will fracture or break apart with rough handling. Since a crack in a porous cup significantly reduces the bubbling pressure by creating a continuous large pore through the wall, damaged samplers will not hold the vacuum needed to draw soil water into the sampler. Verification that a sampler is damaged may be as simple as allowing water to infiltrate to the surrounding soil through the sampler followed closely by an attempt to draw the water back into the sampler. A fast rate of decline in sampler suction may also indicate a fractured ceramic porous cup.

The second concern involves installation of solution samplers at optimal locations beneath lagoons and doing so in a cost effective manner. Hand augering wells at an angle in all but the least competent native soils might be impossible and rocks 3 cm or larger in diameter could also present insurmountable obstacles. Due to compaction requirements and depths to which dairy green water lagoons are excavated, they are likely not constructed in a manner such that wells can be hand augered through previously disturbed materials.

One favorable factor for locating porous cups in optimal locations where leaks might be detected is that lateral flow from an infiltration source commonly occurs in many vadose zone deposits and soils. Lateral spread of water, such as that reported by Glass et al. (2004) (See Figure 3), may significantly improve the prospect for detecting leakage from lagoons with solution samplers.

We propose to address these issues as part of the larger effort to evaluate the use of solution samplers to monitor dairy lagoon leakage. Following is a list of tasks and possible solutions to problems that may be encountered during this evaluation. They are presented here to provide interested parties an understanding of potential problems and solutions associated with implementation of a solution sampler plan, as well as an opportunity to provide feedback.

1) Gain a better understanding of lagoon construction through touring several candidate dairies and reviewing construction plans.
2) Attempt to hand auger wells targeting optimal locations for installing solution samplers. If this fails, consider using a drilling rig with angle-hole capabilities with a hollow stem auger.
3) If the augered soil samples appear dry, consider installing removable tensiometers in the wells to help determine if the soil water tensions are within the operational range of the lysimeter porous cup. The porous cups used on the tensiometers would have the same specifications as those used on the solution sampler.

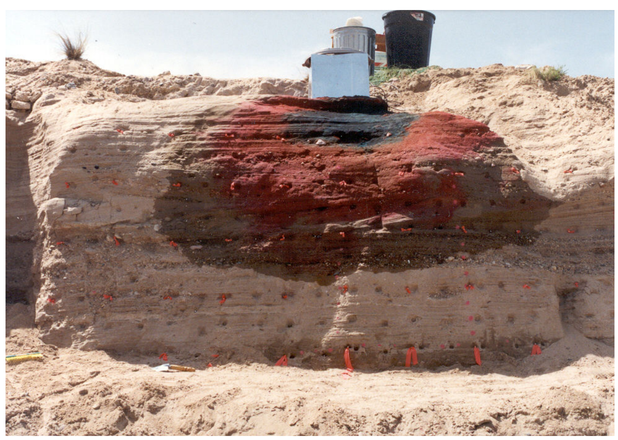

Figure 3. View of a dye stained outcrop of heterogeneous bedded sandy Ancestral Rio Grande deposits illustrating lateral spread of dyed water from a ponded source. Water was infiltrated through the infiltrometer seen at the top of the outcrop. Lateral spread out paced downward movement of dyed water by a factor of two throughout the experiment.

4) If the soil water tensions are beyond the working range of the solution sampler porous cup, devise a procedure to create a wetted bulb around the solution sampler to artificially decrease the soil water tensions to the operational range of the solution sampler. During the ensuing redistribution process where the moisture content of the wetted bulb decreases

as the volume of the wetted bulb increases, investigate the possibility of monitoring soil water tensions with a pressure transducer installed in one of the sampling tubes on the solution samplers. If this is successful, the rate of change in tension may indicate the effectiveness of artificially decreasing the soil water tension for the purpose of enabling sampling with a solution sampler.

5) If the soil water tensions are within the working range of the solution sampler porous cup, (i.e., the porous cup does not desaturate) and no sample can be obtained, consider a long term sample collection plan and use a no sample result as an indication of a properly operating liner. Test the sampler for proper operation by infiltrating water into the soil through the sampler and then follow normal sampling procedures to retrieve a portion of the infiltrated water. If water can be drawn back into the sampler shortly after infiltrating water, then the sampler is operating correctly.
6) If the samplers consistently produce samples following installation without the need to infiltrate water through the sampler as described in the two situations above, have the samples analyzed for NO_3-N and other potential organic contaminants to determine if the sample water originates from the lagoon.
    a. If a sampler installed below a clay liner produces a sample and the sample tests positive for NO_3-N or other organic contaminants, determine if the sample represents normal and acceptable seepage from the lagoon or represents unacceptable leakage. Installation of three or more solution samplers in low-risk leakage areas along with three samplers in high risk areas may help to resolve the leakage versus normal seepage issue.
    b. If samples collected below a synthetic liner test positive, consider the positive result a definite sign of liner failure.
    c. Implement a long-term sampling program to evaluate the potential of plugging the porous ceramic cup with soil and organic particles.
7) Consider installing stainless steel solution samplers if concerns arise about the fragility of porous ceramic porous cups and the soil is fairly moist. Stainless steel samplers have a significantly lower bubbling pressure than ceramic cups (500 mb versus 2 bar).

Conclusions

1) Monitoring of the vadose zone beneath dairy lagoons would provide early detection of leaks in lagoon liners and therefore could lead to greatly reduced aquifer contamination and remediation costs.
2) Of the current technologies available for monitoring the vadose zone beneath dairy lagoons, solution samplers may be the most cost effective technology currently available.
3) Solution samplers have been in use for several decades and have been shown to be effective at collecting soil solutions for a variety of agricultural and contaminant monitoring purposes.
4) Ceramic porous cups have been used with great success and are preferred over stainless steel due to the higher bubbling pressure and lesser cost.
5) Solution sampler failure from damaged ceramic porous cups can be easily prevented with careful handling such as that needed for any durable glass product.
6) Successful installation of solution samplers beneath existing dairy lagoons depends on ease of hand augering or drilling near the periphery of the lagoon.

7) Lateral spreading of infiltrated water from an infiltration source is commonly observed in the vadose zone and could work in favor of detecting liner leaks with solution samplers.
8) Procedures can be implemented to evaluate proper operation if samplers do not produce samples upon installation. Lack of a sample may result from dry soils and may indicate no leakage from the lagoon.

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