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ABSTRACT

This research investigated the effect of three anaerobic swine-waste lagoons on the quality of nearby ground water. The lagoons, in the Coastal Plain region of Virginia, were located on soils with high water tables and with varying drainage characteristics. Over a 14-month period in 1974 and 1975, ground water samples were taken from wells located at various depths and distances from the lagoons. These samples then were analyzed to determine the extent of contamination due to the lagoons. The biological constituent analyzed was the number of fecal coliform bacteria; chemical constituents analyzed were concentrations of Cl, Cu, Mn, NH_4 —N, NO_3—N, PO_4—P, and Zn.

Research findings showed that the quality of ground water was affected least around one lagoon constructed at ground level in a poorly drained soil with a clay subsoil. No ground water contamination was found more than 3 m from this lagoon. In contrast, ground water around two lagoons constructed with embankments above ground level, one in a sandy clay loam subsoil and the other in a sandy subsoil, showed traces of swine-waste components as far away as 30 m. Pollutant levels in ground water around the former lagoon were below U.S. Public Health Service drinking water standards, while pollutant levels around the latter lagoon exceeded those standards on many occasions. These experimental results indicate that seepage may occur from lagoons with embankments above ground level in sandy soil, and that biological sealing in such lagoons may not sufficiently protect shallow aquifers from contamination.

Key Words: Pollutant Movement, Ground Water Monitoring, Lagoon Seepage, Soluble Nutrients, Waste Disposal.

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INTRODUCTION

Swine production in Virginia is concentrated in the Coastal Plain region where confinement production practices are common. One inherent problem in intensive swine production is disposal of large quantities of wastes that are concentrated in a relatively small area. A large portion of the wastes from swine confinement areas are drained into anaerobic lagoons. Use of anaerobic lagoons for swine waste disposal is practical because they are inexpensive to construct and require a minimal maintenance. Very often these lagoons are constructed by simply excavating soil from the desired site, with little consideration of soil profile characteristics. Experimental results in the literature [Hart and Turner, 1965; Loehr, 1968; Scalf et al., 1973] indicate that seepage is expected to occur from these lagoons. Research by Davis et al. [1973], Nordstedt et al. [1972], and Sewell et al. [1975] indicated that seepage from anaerobic animal waste lagoons is negligible and that the seepage has only a slight effect on ground water quality.

A human health hazard could occur from drinking water where an excessively high amount of contamination moves by seepage from an anaerobic swine waste lagoon into ground water. No conclusive evidence was found in the literature that seepage from anaerobic swine waste lagoons poses a significant health hazard.

The research described in this report involved the Departments of Agronomy, Agricultural Engineering, and Animal Science at Virginia Polytechnic Institute and State University, and the university's Tidewater Research and Continuing Education Center. Its purpose was to determine the effect of anaerobic swine waste lagoons on ground water quality in the Coastal Plains region of Virginia. Specific objectives of the research were:

1. To determine the amount, distance, and rate of movement of pollutants from anaerobic lagoons into ground water, and
2. To measure the variability in ground water contamination as affected by inherent soil drainage characteristics.

LITERATURE REVIEW

I. Artificial Sealing of Anaerobic Lagoons

According to the Colorado Cooperative Extensive Service [1971], the most important aspect of animal waste lagoon design is to prevent seepage. Soil Conservation Service [1972] guidelines for lagoons site selection are similar to those used for farm pond site selection. The lagoon should be located on a heavy-textured soil or on a soil that can be made impermeable. Measures for sealing are recommended if percolation is expected even though biological sealing is anticipated with time [Midwest Plan Service, 1975]. Sealing may be accomplished by compacting the original soil at the lagoon site, or by lining the lagoon with a flexible membrane or a clay blanket. Seepage from waste lagoons is reduced to practically zero through use of such flexible membranes as polyethylene plastic, pigmented polyvinyl, butyl rubber, or concrete slabs having watertight joints [Miller, 1971].

Nienaber et al. [1975] studied the effectiveness of a 0.15-mm polyethylene plastic liner, bentonite clay, and soil cement in sealing a feedlot catchment basin. Unless ruptured or punctured, the plastic liner was quite effective in preventing seepage. Bentonite clay formed a good seal when wet, but cracked on drying. This was of considerable concern because the fluctuating water level in the basin caused cracking of the banks and subsequent seepage. The soil cement was effective as a sealant for over five years, however, its high initial cost was a major problem.

It has been shown that clay blankets are not impermeable to water [van der Leeden et al., 1975]. Van der Leeden et al. calculated the magnitude of water loss from an 8-ha lagoon with a 3-m depth and a 60-cm clay liner. Assuming that the clay lining had a permeability of 0.004 cm/day, they estimated tht 57,000 m^3 of wastewater would be lost through seepage annually. Contamination of a well placed 300 m from the lagoon would not occur for at least five years (assuming a ground water flow of 15 cm/day.) In five years, 285,000 m^3 of wastewater would have been lost by seepage.

II. Infiltration Losses from Anaerobic Lagoons

The use of farmyard manure to seal farm ponds was studied by Jamison and Thorton [1963]. Two days after a manure treatment the hydraulic conductivity of the pond bottom was reduced from 0.039 cm/day to 0.01 cm/day. Within a week, the hydraulic conductivity was further reduced to 0.003 cm/day. Subsequent testing showed that the reduction in hydraulic conductivity was not due to the high ammonia content of the manure.

Davis et al. [1973] studied the effect of manure water on the sealing of a dairy lagoon. The soil in the lagoon was compacted before the addition of manure water. Infiltration rates decreased 200-fold after the introduction of the manure water. The authors observed that the addition of manure water gave rise to a bottom slime and sludge layer. They indicated that the bottom slime resembled crankcase oil in appearance.

Hart and Turner [1965] studied infiltration losses from pilot lagoons, which were 2.4 m deep and 1.2 m in diameter. The pilot lagoons had concrete sides and a natural soil bottom. Infiltration losses from manure waters varied from 18 to 45 percent of the influent solids [Hart and Turner, 1968].

Infiltration rates of 17 manure ponds in the San Joaquin Valley of California were studied by Meyer et al. [1972]. Minimal infiltration rates were observed from these lagoons. The highest infiltration rate of 1 mm/day was found for a lagoon located on coarse, sandy soil. No contamination of ground water was reported from the 17 manure ponds.

III. Natural Sealing of Anaerobic Lagoons

Oliver et al. [1975], using tensiometer cups placed 0.6, 1.2, 1.8, 2.4, and 2.9 m beneath a dairy lagoon, found no contamination at depths greater than 2.4 m. Sealing of the lagoon was determined by measuring the hydraulic gradient between the tensiometer cups at 0.6- and 2.4-m depths. The lagoon was considered sealed when the hydraulic gradient was zero. Sealing of the lagoon was accomplished within 60 days of filling with manure water. The authors reported that this sealing time was considerably greater than that observed for other lagoons in the area. Since normal sealing time was 30 days, they postulated that the delayed sealing reflected removal of solids by screening before entry of the manure water into the lagoon.

Physical clogging of porous media used for deep infiltration treatment of wastewater is due to particles being trapped in four different types of retention sites [Herzig et al., 1976]. The authors characterized these as surface, crevice, constriction, and cavern sites. Processes operative in capture of particles in retention sites were referred to as sedimentation, inertia, hydrostatic effect, diffusion by Brownian motion, and direct interception. It was described that capture by sedimentation and inertia are attributable to the different densities of the particles and the fluid medium. In capture by the process of sedimentation, the particles fall due to the force of gravity, whereas capture by inertia is due to the inability of particles to change direction at the same rate as the fluid medium. Hydrostatic effects reflect the nonsphericity of the particles, causing a lateral migration to the retention sites. Capture by direct interception is caused by the exclusion of particles from paths smaller than themselves. Diffusion by Brownian motion may introduce the particles into retention sites not commonly transversed by the fluid stream. Particles retained by retention sites require certain forces to prevent their escape. Retention forces include axial pressure of the fluid; and frictional, surface, and chemical forces. Escape from the retention sites is due to local variations in flow or pressure, or to similar variations in the entire bed. Reversal of flow can cause considerable release of particles trapped in the retention sites.

Chang et al. [1974] studied the sealing mechanism of a newly construced dairy lagoon. They used 30-m long and 5-cm wide columns packed with acid washed sand or with sandy, loamy, or silty-clay soils. The columns were placed with their exposed surfaces level with the lagoon bottom. Water was added to the lagoon 48 hours prior to the introduction of dairy waste. The columns were recovered at various times after the introduction of the dairy waste. Chemical constituents and hydraulic conductivity were determined for the entire columns and for five cm sections of the columns. Hydraulic conductivity in the soil columns was undetectable after a submergence time of 30 days. The hydraulic conductivity of the acid washed sand columns was reduced from 14.5 cm/hr to 0.15 cm/hr after a submergence time of 60 days. Hydraulic conductivity determined in column sections indicated that sealing occurred in the top five cm within three days after dairy waste was added to the lagoon. Sealing of the lower sections of the columns increased with time. The authors attributed the reduction of the hydraulic conductivity to physical clogging of the soil pores initially and to biological sealing with time. Biological sealing was considered the most important sealant factor. Allowing the columns to dry for seven days returned the hydraulic conductivities to their initial values.

Concentrations of NO_3—N, Na, and Cl in the columns increased during the first 30 days, appeared to plateau after 30 to 60 days of submergence, and declined thereafter [Chang et al., 1974]. The authors explained this behavior as movement of the chemical constituents with the wastewater prior to the establishment of the biological seal. The plateau region was attributed to establishment of equilibrium between the chemical concentrations of the seepage and that of the surrounding soil. As the flow of seepage decreased due to the sealing of the lagoon, the equilibrium was destroyed and there was net movement of ions out of the columns. This trend was followed more closely by Cl than other chemical constituents due to its greater mobility in soil.

IV. Ground Water Contamination from Anaerobic Lagoons

Sewell et al. [1975] studied the effect of a newly constructed dairy lagoon on ground water quality. Nitrate—N and Cl concentrations in ground water varied widely before and after the operation of the lagoon. Concentrations of NO_3—N and Cl in ground water increased during the first two months of lagoon operation, and decreased thereafter. The authors did not draw any concrete conclusions because of the short duration of the study.

Nitrate concentration beneath a playa lake used as a catchment basin for feedlot runoff did not increase after five years of operation [Clark, 1975]. Chloride concentration increased from 25 to 125 ppm at a 3-m depth beneath the basin. The Cl concentration in the basin was greater than 1,000 ppm. The observed increase in Cl concentration of 100 ppm in soil solution after five years indicated slight seepage from the basin.

Miller, Robinson, and Gallagher [1976] studied the accumulation of nutrients beneath four anaerobic swine lagoons. High NH_4—N concentrations ranging from 600 to 1,000 ppm were found immediately below the lagoons. The ammonium concentrations decreased to background levels 40 cm below a lagoon that was in operation for two to three years in a fine textured soil. Ammonium—N concentrations were in excess of 200 ppm at a depth greater than 140 cm beneath lagoons in medium-textured soils, and at a depth greater than 400 cm beneath a lagoon in a coarse-textured soil. These lagoons constructed in the medium and coarse texture soils were in operation for eight to ten years. The authors indicated that, if aerobic conditions were to exist below the lagoons, considerable nitrification would be expected with the subsequent production of high amounts of nitrates. Nitrates produced during nitrification would be subject to leaching into the ground water.

The effect of municipal waste stabilization ponds on ground water quality was studied by Preul [1968]. Wells were driven at various depths and distances from the stabilization ponds. Selection of ponds for the study was based on their high infiltration rates. Phosphates were not above background levels at distances greater than 10 m from the stabilization ponds, whereas NH_4—N concentrations dropped to background levels within a distance of 92 m. Concentrations of NO_3—N were higher in ground water sampled 92 m from the ponds than in ground water obtained from wells placed upstream from the apparent ground water flow. The nitrate concentration was below the United States Public Health Service (USPHS) drinking water standards. Concentrations of alkyl benzene sulfonate decreased from the ponds, but were greater than the USPHS drinking water standards of 0.5 ppm at a distance of 92 m. Concentrations of NH_4—N, NO_3—N, and PO_4—P in the waste stabilization ponds varied from 4 to 21 ppm, 4 to 21 ppm, and 1 to 6 ppm, respectively.

Nordstedt et al. [1971] studied the effect of a multistage dairy lagoon system on ground water quality in a sandy soil with a high water table. Wells were driven at distances of 4.5, 15, and 34 m from the lagoon and at depths of 2.4 and 3 m. A reference well was placed in an effluent irrigated pasture. The effluent irrigation was taken from the third stage lagoon. Data obtained for four months indicated that ground water was affected at 4.6 and 15 m from the primary anaerobic lagoon, but not at 30 m. The authors noted that the study was anticipated to continue and further data was needed before any firm conclusion would be drawn.

MATERIALS AND METHODS

Three anaerobic swine waste lagoon sites varying in drainage characteristics were selected for the ground water monitoring. These lagoons were located in the Coastal Plain region at the Virginia Swine Evaluation Center (VSEC), Suffolk, Virginia; at the Tidewater Research and Continuing Education Center (TRACEC), Suffolk, Virginia; and at a private farm in Suffolk, Virginia. The lagoons were located on soils with high water tables and with surface textures ranging from sandy loam to fine sandy loam.

I. Well Locations

Unperforated wells were placed at various depths and distances from the lagoons for ground water monitoring. These wells were waterjetted to depths of 3, 4.6, and 6 m at distances of 3, 15, and 30 m from the lagoons at the VSEC and the private farm, and at distances of 3 and 15 m from the lagoon at the TRACEC. Check wells were established in a fenced weather observation center at the TRACEC. The check wells were greater than 1.2 km from the lagoon and were more than 100 m from any septic system drainfield.

The wells were located in the apparent direction of ground water flow. Topographic and surface features were used to determine the placement of the wells. Wells were located around the four sides of the lagoon at the VSEC (*Figure 1*) because of the difficulty in assessing the natural surface drainage pattern. Three sets of wells were placed in the apparent direction of ground water flow at the TRACEC (*Figure 2*). Two sets of wells—noted as Series I and Series II—were located at the private farm lagoon site (*Figure 3*). Series I was located in a depressional area while Series II was located in a higher, better-drained area.

II. Well Description and Ground Water Sampling

Polyvinylchloride (PVC) pipe of 5-cm diameter was used as the well casing. The unperforated wells were waterjetted about 15 cm deeper than the well casing. Pea gravel was inserted into the well to form a 10-cm layer in the casing. This procedure was followed to prevent undue sediment uptake during sampling.

The wells were fitted with a PVC plastic cap. A sampling tube consisting of 1.8 cm diameter PVC pipe was inserted through the cap to a depth of 10 cm above the pea gravel. A 2.5-cm long and 1.8-cm diameter PVC tube was inserted through the cap to serve as an entry port for water table measurements. Rubber cement was used to seal the cap-pipe junctions to prevent the entry of either dust or rainwater.

Ground water was sampled monthly from the 64 wells from September, 1974, through January, 1975, and bi-monthly thereafter through November, 1975. A study was completed to determine rates of movement of contaminants to wells located at the VSEC. Ground water was sampled on four consecutive days in December, 1974, for this study. All samples were obtained using a "Sta-Rite" shallow well jet pump fitted with a 46-kg check valve and trap assembly (*Figure 4*). Wells were purged one day before sampling to remove standing water. The samples were collected in steam-sterilized, acid-washed quart mason jars.

Temporary wells were placed around the three lagoons to evaluate whether wells were too deep to monitor contamination. These wells were augered to a depth of 15 cm below the ground water surface. The wells were located at distances of 3 and 4.6 m from the lagoons at the VSEC and the TRACEC; and at 3, 15, and 34 m from the lagoon at the private farm. Grab samples of ground water were taken from these temporary wells.

Ground water was sampled from perforated wells waterjetted to a depth of 3.6 m at distances of 0, 0.8, 1.5, 2.3, 3, 3.8, 4.6, 6, 7.6, 10.7, 13.7, 16.8, 22.9, 24.0, and 36.6 m from the lagoons at the TRACEC and the private farm. These wells were established for a related study and placed parallel to the original wells [Bucklew, 1976]. Ground water samples were obtained from these wells by aforementioned methods.

III. Piezometric Maps

Water table heights were measured on March 24, 1976, in temporary wells augered to a depth of 15 cm below the water table surface and at various distances from the lagoons. The wells were augered around the four sides of the lagoons. Ground elevations, relative to the effluent level in the lagoons, were determined using a surveyor rod and level. Piezometric maps of the lagoon sites were drawn from these measurements (*Figures 5, 6, and 7*). The direction of the ground water flow is assumed to be orthogonal to the equipotential lines. This map was used to compare the apparent ground water flow with the direction predicted by the relative water table heights.

IV. Ground Water Analyses

Ground water samples obtained from the perforated and unperforated wells were analyzed in duplicate for fecal coliform bacteria and for concentrations of Cl, Cu, Mn, NH_4—N, NO_3—N, PO_4—P, and Zn. Fecal coliform bacteria numbers were determined by the millipore membrane filter technique [APHA, 1971]. The samples for fecal coliform determinations were transported to the laboratory at the TRACEC, and the analysis was initiated within two hours after the ground water sampling. Samples were frozen and transported to Blacksburg for chemical analyses. Nitrate—N was determined by a phenoldisulphonic acid method [APHA, 1971]. Concentrations of Cl in the ground water were determined with an Orion specific ion electrode [Hindin, 1975], and concentrations of NH_4—N with an Orion gas sensing electrode [EPA, 1974]. The electrodes were coupled to a Beckman Century SS-1 pH meter having an expanded scale. The NH_3 electrode was wrapped in a grounded piece of aluminum foil to reduce fluctuations during the readings [Mertens et al., 1975]. Soluble PO_4—P was determined after filtering the sample through a 0.45 μ filter by an ascorbic acid single reagent procedure [APHA, 1971]. The concentrations of Cu, Zn, and Mn were determined by atomic absorption spectrophotometry. The samples were prepared for analyses by filtering through a Whatman No. 42 filter paper and then by drying them down a 20-ml aliquot. The dried sample was taken up in 20 ml of 0.5 N HCl, and stored in plastic bottles until analyzed. Chloride concentrations were measured in ground water samples obtained from the temporary wells. The Cl concentrations were analyzed in the same manner as the other ground water samples.

V. Soil Samples

An experiment was conducted to determine the effect of anaerobic swine waste lagoons on exchangeable NH_4—N and NO_3—N in soils. Soil samples were obtained for this experiment at 0.3-m intervals, excluding the first 0.3 m, to a depth of 1.2 m at distances of 3 and 15 m from the lagoon at the TRACEC; and at 3, 15, and 34 m from the lagoon at the private farm.

Exchangeable NH_4–N and NO_3–N in soil were determined by extraction with 2 N KCl and then by a stream distillation chemical analysis [Bremer, 1965].

VI. Statistical Analyses

Differences in biological and chemical constituents in ground water and in soil were evaluated by an analysis of variance and by the Duncan's Multiple Range Test. The statistical analyses were performed on an IBM 360 computer utilizing the SAS computer program [Service et al., 1972]. For the statistical analyses, constituents in ground water that were below the detection limits were considered to be the following concentrations in ppm: Cu, 0.09; Mn, 0.49; NH_4–N, 0.09; NO_3–N, 0.19; PO_4–P, 0.05; and Zn, 0.09.

RESULTS AND DISCUSSION

Holl [1972] identified NO_3—N, NH_4—N, Cl, PO_4—P and permanganate number as being indicators of ground water pollution. The latter is similar in principle to chemical oxygen demand. Nitrate—N, NH_4—N, Cl, and PO_4—P are by-products of the degradation of fecal matter. Fluctuating concentrations of these constituents indicate that either animal or human waste has access to a water supply. The pollution indicators described above, with the exception of permanganate number, were determined in ground water samples for this investigation.

I. Virginia Swine Evaluation Center Site

The lagoon at the VSEC *(Figure 1)* is located on an Elkton very fine sandy loam (Typic Ochraqult, clayey mixed, mesic). This soil is poorly drained with a very fine sandy loam surface and a clayey subsoil. The lagoon is constructed predominately below ground level in this soil with a high water table. The lagoon has been in operation for over eight years.

Ground water sampled at various depths and distances from the lagoon contained <0.10 ppm Cu and Zn, <0.50 ppm Mn, <0.06 ppm soluble PO_4—P, and <0.20 ppm NO_3—N. Mean NH_4—N concentrations in wells located beyond three m from the lagoon were <1.0 ppm *(Table 1)*. Fecal coliform bacteria were detected sporadically, but numbered $<100/100$ ml in ground water after the first sampling. High fecal coliform counts obtained in the first sampling were probably due to contamination during well installation. In no case were there more than two positive fecal coliform bacteria counts for any well during the sampling period.

Data from one well was not included in the previous discussion. This well was located three m from the lagoon at a depth of three m in the southeast (SE) set *(Figure 1)*. Consistently high numbers of fecal coliform bacteria and concentrations of NH_4—N, Cl, and PO_4—P were found in ground water sampled from this well. Ground water obtained from this well was similar in color to that of the effluent in the lagoon at the various sampling times. Channelling from the lagoon was considered as a possible source of the contamination. A well was waterjetted to the same depth and 1.5 m from the contaminated well to determine if seepage was the cause of the contamination. This well was uncontaminated; thus discounting seepage as the probable cause of the contamination.

With the exception of the contaminated well, mean Cl concentrations of the ground water sampled from the SE well set *(Figure 1)* were <20 ppm, whereas mean Cl concentrations in the northwest (NW) well set *(Figure 1)* ranged from 18 to 148 ppm *(Table 2).* Concentrations of Cl decreased with distance in the NW set, but did not reach the low levels observed in the SE set. The higher Cl concentration was found in the direction of ground water flow as predicted by the piezometric map of the lagoon site *(Figure 5).*

Ground water obtained from temporary wells augered at 3 and 15 m from the lagoon had mean Cl concentrations ranging from 10 to 90 ppm *(Table 3).* Mean concentrations exceeding 80 ppm occurred in ground water sampled with three m of the lagoon, but decreased to <20 ppm at 15 m. Temporary wells located near the NW well set, 15 m from the lagoon, contained <20 ppm, indicating that the unperforated wells were not too deep for the ground water monitoring.

The SE well set *(Figure 1)* was used to study the rate of pollutant movement from the lagoon. At the time of the study these were the only wells located at the site and were in the estimated direction of ground water flow. No consistent differences in Cl concentration were found during four consecutive days of sampling following a relatively heavy loading period *(Table 4).* Subsequent construction of a piezometric map of the area indicated that these wells were located upstream from the ground water flow.

Although Holl [1972] warns of the danger of using concentrations of one constituent as an indicator of pollution, the high Cl concentrations in the NW well set as compared with the SE well set *(Table 2)* might indicate ground water contamination. Various explanations can be given for the low values of NH_4—N, NO_3—N, PO_4—P, Cu, Zn, and Mn as compared with the relatively high Cl values. The Cl anion does not undergo either biological modifications or chemical precipitation reactions within the soil and moves readily with the soil water. Movement of NH_4—N is retarded due to adsorption by clays, to biological interconversions, and to uptake and utilization by plants and microorganisms. Undetectable levels of NO_3—N may reflect the low nitrate concentrations in the lagoon and the soil conditions that are unfavorable for nitrification. Nitrates that might have been formed would be readily sorbed and utilized by plants. Insoluble Cu, Mn, P, and Zn compounds would be expected to occur at the pH level in the lagoon [Humerik, 1972]. Precipitation of these compounds would greatly curtail movement of the ions from the lagoon.

II. Tidewater Research and Continuing Education Center Site

The lagoon located at TRACEC *(Figure 2)* was built in a Dragston fine sandy loam (Aquic Hapludult, coarse-loamy, siliceous, thermic). The Dragston soil is somewhat poorly to poorly drained with a fine sandy loam surface and a sandy clay loam subsoil. The lagoon was constructed partly above ground level with embankments approximately 2 m above the natural ground surface. Operation of the lagoon began in August, 1974. It is a two-stage lagoon consisting of an anaerobic cell connected to an effluent holding pond by an overflow pipe.

Concentrations of Cu, Zn, Mn, and soluble PO_4—P in ground water sampled at this site were below the detection limits of the chemical procedures used in this study. Mean NH_4—N concentrations were <1.0 ppm *(Table 5)* for all the wells, except one located in the center well set at a depth of 3 m and a distance of 3 m from the lagoon *(Figure 2)*. Ammonium—N concentrations in ground water from this well ranged from 0.9 to 21.0 ppm with a mean of 4.5 ppm.

Ground water sampled at a depth of 3 m from the check well had a lower mean NO_3—N concentration than that sampled 3 m from the lagoon, and had a similar mean NO_3—N level as that sampled 15 m from the lagoon *(Table 5)*. Mean NO_3—N concentrations at the 4.6-m depth did not differ from that of the check well at distances of 3 and 15 m from the lagoon. However, the check well had a higher NO_3—N concentration at the 6-m depth than wells at the 3- or 15-m distances. The high NO_3—N concentration of the check well at the 6-m depth was probably due to local ground water conditions that were not associated with seepage from the lagoon.

Water levels in unperforated wells placed 15 m from the lagoon ranged from 46 to 91 cm in the well that was 3 m deep, and from 112 to 155 cm in wells that were 4.6 and 6 m deep *(Table 6)*. These data indicate a restricting barrier between a depth of 3 and 4.6 m. In constructing the lagoon, the barrier may have been disrupted allowing contamination from the lagoon to enter the aquifer below the restricting layer. Water table measurements in the check wells also indicated the presence of a restricting barrier. This barrier was between 4.6 and 6 m deep *(Table 7)*. Nitrate concentrations below the barrier were consistently higher than those above the restricting layer. The higher nitrate concentration might have been due to the partitioning of two shallow aquifers or the result of leaching from the shallower depth.

The direction of ground water flow estimated from topographic and surface features agreed with that predicted from the piezometric map of the area *(Figure 6)*. Ground water samples were obtained at various distances around the lagoon to ascertain if the unperforated wells were too deep for adequate ground water monitoring. Data from these samples showed that the wells were not placed too deep *(Table 8)*. Chloride concentration data from these wells supported the predicted direction of ground water flow.

Mean Cl concentrations in the check wells were less at all depths than in the wells that were 3 and 15 m from the lagoon *(Table 5)*. The mean Cl concentrations decreased with distance at the 3-m depths. No differences occurred in wells 3 and 15 m from the lagoon at depths of 4.6 and 6 m. Observations obtained in September, 1975, were excluded from the calculations of the check means. Rejection of the data was due to the magnitude of the difference of the Cl concentration from the September sampling and the other sampling dates. The Cl concentrations in September were 273 and 435 ppm in the check wells at depths of 3 and 4.6 m, respectively. Less than 10 ppm Cl was observed on the other sampling dates for the check wells. The high Cl concentrations in the September samples from these wells might have been due to insufficient rinsing of the HCl used to acid wash the collection bottles.

Ground water sampled from the perforated wells usually had Cl concentrations <100 ppm within 7.6 m of the lagoon and approached background levels at 36.6 m *(Table 9)*. Nitrate—N concentrations were high in the embankment but decreased to <2 ppm within 4.6 m from the lagoon. The high Cl and NO_3—N concentrations in the perforated wells may indicate seepage from the sides of the lagoon. Seepage may be due to the incomplete biological sealing and to the destruction of the seal with drying as the changes in effluent levels exposed the lagoon sides.

Seepage from the sides of the lagoon would have a larger volume of unsaturated soil through which to travel than seepage from the bottom. Nitrification would be greater in seepage from the former source as indicated by NO_3—N concentration data from unperforated and perforated wells *(Tables 5 and 9)*. The decrease in NH_4—N and NO_3—N concentrations with distance may be due to dispersion and dilution effects and to uptake and utilization by plants.

Mean exchangeable NH_4—N was greater in soil samples obtained 3 m from the lagoon at a depth of 90 to 120 cm, than in soils sampled at the same depth at a distance of 15 m *(Table 10)*. The mean exchangeable NH_4—N values did not differ with distance from the lagoon at the other depths and were below 10 ppm. No differences occurred in the exchangeable NO_3—N at the various distances *(Table 11)*.

The Cl and NO_3—N concentrations in ground water indicated seepage from the lagoon located at the TRACEC. However, the overall level of these pollutants in ground water was not exceedingly high. For this reason, it is concluded that seepage from the lagoon does not pose a threat to the underground water supplies in the area.

III. Private Farm Site

The lagoon located at a private farm in Suffolk was constructed partly above ground with embankments of 1 to 2 m above the original soil level. It is located in a sandy soil with a high water table. Wells were located in a poorly drained area *(Series I)* and in a somewhat poorly drained area *(Series II)*. The wells were located at distances of 3, 15, and 30 m from the lagoon, and at depths of 3, 4.6, and 6 m *(Figure 3)*. Wells in Series II were located at a higher elevation than those in Series I.

Copper, Zn, Mn, and soluble PO_4—P generally were below the detection limits for the chemical tests employed in this study. Fecal coliform bacteria were not detected after the first month-sampling except for two isolated observations. Contamination during well installation was believed to be the cause of the positive fecal coliform bacteria test during the first sampling.

Well Series I—Ground water obtained from these wells on the 10 sampling dates contained mean NH_4—N concentrations ranging from 0.3 to 357.9 ppm *(Table 12)*. The mean NH_4—N content was greater at a 3—m depth and a 3—m distance from the lagoon, than at the same depth and 15— and 30—m distances. Although not significantly different, NH_4—N concentrations at the 4.6—m depths were generally lower 3 m from the lagoon than at the 15— or 30—m distances. Ammonium—N concentrations at the 6—m depth were less at the 30—m distance than other distances. The NH_4—

N concentration in ground water obtained from this well was <0.5 ppm. Hydraulic conductivity measurements for this well were 2.5 times less than those found for an adjacent well at a 3—m depth, and 30 times less than for the adjacent well at a 4.6—m depth. These measurements and NH_4—N data *(Table 12)* indicate that the well is isolated from the generally contaminated flow.

Chloride concentrations from Well Series I were generally >100 ppm. Two wells had Cl concentrations of <100 ppm. These wells were located 30 m from the lagoon and at depths of 4.6 and 6 m. The former well had a mean Cl concentration of 72 ppm, and the latter had a mean Cl concentration of 92 ppm *(Table 13)*. Chloride concentration in ground water from the latter well was under 12 ppm prior to September, 1975, and was 427 and 177 ppm in September and November, respectively. This trend from low concentration to a relatively high concentration was not observed for the other wells in Series I and for other constituents determined in the same well. The cause of the Cl fluctuation is unknown. Contamination of the sampling apparatus might be expected if one observation gave abnormally high readings, but the probability of it happening twice and in consecutive sampling periods is small. Concentrations of NO_3—N did not indicate the same fluctuations. These data suggest that a pollution front did not reach the well.

The USPHS recommended drinking water standard of 250 ppm for Cl [EPA, 1973] was exceeded in ground water from the well that was 3 m deep and 3 m from the lagoon on all sampling dates, except November, 1975. Chloride concentrations in the ground water from this well were greater than that sampled from wells at the same depth and at 15 and 30 m from the lagoon. No differences were observed in mean Cl concentrations at 3-, 15-, and 30-m distances for ground water sampled at 4.6- and 6-m depths *(Table 13)*.

Ground water from a set of perforated wells parallel to Series I exhibited an unusual Cl concentration pattern. In this series, Cl concentrations were highest near the lagoon, decreased with distance, and reached a second maximum at 16.8 m from the lagoon *(Table 14)*. The presence of two maximums indicated two sources of Cl contamination: one concentrated at the embankment and probably due to seepage from the lagoon, and another source located at 16.8 m from the lagoon. The unsaturated soil in the embankment would be conducive to nitrification. Nitrate—N concentration ranged from 35.5 to 68.1 ppm in ground water obtained from wells located between 0 and 3 m from the lagoon, and dropped to undetectable levels beyond 6 m *(Table 14)*. The decrease in NO_3—N concentration beyond 4 m can be attributed to: (a) denitrification as the NO_3—N entered waterlogged anaerobic soil; (b) dilution and dispersion; and (c) uptake and utilization by plants and microorganisms. High NO_3—N concentrations in ground water sampled from wells 15 and 30 m from the lagoon and at 4.6— and 6—m depths may be due to the movement of NO_3—N from the lagoon embankment.

Mean NO_3—N concentrations in ground water obtained from wells 3 m from the lagoon were the same or less than that obtained from wells located at distances of 15 and 30 m *(Table 15)*. Higher NO_3—N concentrations were found 30 m than 15 m from the lagoon at a depth of 4.6 m. The USPHS drinking water standard of 10 ppm for NO_3—N [USPHS, 1962] was exceeded in ground water from these wells. Mean NO_3—N concentration was greatest 15 m from the lagoon at the 6—m depth. Higher nitrate concentration in ground water farther from the lagoon might be interpreted as a greater rate of nitrification with increasing distance from the lagoon. This does not seem likely due to the poorly drained nature of the area. Nitrate from a source other than the lagoon cannot be discounted. The direction of ground water flow as determined by the piezometric map *(Figure 7)* of the lagoon site indicates possible ground water movement from a nearby field. This field has been used for the disposal of anaerobic swine waste lagoon effluent. Nitrification would be expected to occur in the field and may be leached beyond the roots of the crop plants into the ground water. This effect would be observed in wells farther from the lagoon due to the hydrostatic pressure induced by the presence of the lagoon.

Mean concentrations of Cl in ground water from temporary wells augered below the water table ranged from 2 to 45 ppm *(Table 16)*. A decrease in Cl concentration occurred with distance from the lagoon. The low Cl levels of the samples as compared to those in unperforated wells indicate that the observation wells were not too deep for the ground water monitoring.

Mean exchangeable NO_3—N concentration from soil sampled 3 m from the lagoon at a depth of 120 to 150 cm was higher than that from soil sampled at distances of 15 and 34 m *(Table 17)*. No differences between distances were observed for the other depths. Soil sampled at 30 to 60 cm had a higher exchangeable NH_4–N content 3 and 15 m from the lagoon than at 34 m *(Table 18)*. No differences with distance were observed for the other depths.

Well Series II–Ammonium–N concentrations of ground water obtained from wells in this series were <1.0 ppm for 88 of the 90 observations. No differences in mean NH_4–N concentrations occurred in ground water sampled at the various depths and distances from the lagoon *(Table 12)*. Mean Cl concentrations did not differ with distance at the 4.6– and 6–m depths *(Table 13)*. The mean Cl concentration was higher in ground water sampled 30 m than from either 3 or 15 m from the lagoon at a depth of 3 m. The high Cl concentration is probably due to a localized ground water condition rather than to seepage. Chloride concentrations in samples from perforated wells parallel to this series were relatively high for the 0– to 3–m distances from the lagoon and decreased to background levels at 36.6 m *(Table 19)*. Unlike Series I, no second maximum was observed in this series of wells.

Mean NO_3–N concentrations in ground water sampled from wells at 3– and 4.6–m depths and 3 m from the lagoon exceeded or approached the USPHS standards for drinking water. The mean NO_3–N concentrations decreased with distance in wells that were 3 and 4.6 m deep *(Table 15)*. Ground water sampled at a 6–m depth was higher in NO_3–N at 15 and 30 m from the lagoon than at 3 m. Ground water sampled from perforated wells 0 to 3 m from the lagoon parallel to this series ranged from 20 to 100 ppm in NO_3–N *(Table 19)*. The NO_3–N levels decreased with distance from the lagoon, but were 5.1 or higher within a distance of 13.7 m and then approached undetectable amounts at 36.6 m.

Nitrate–N concentrations were generally higher in ground water sampled from well Series II as compared with well Series I *(Table 15)*. The higher NO_3–N levels may be due to a difference in elevation. Wells in Series II were located at a higher elevation than the depressional site of Series I. The former area probably was more conducive to nitrification.

Mean exchangeable NH_4–N concentrations in soil sampled at a depth of 120 to 150 cm was greater 15 m from the lagoon than at 3 m *(Table 20)*. Differences in mean exchangeable NH_4–N were not found in the soil obtained 3 and 15 m from the lagoon at the other depths. No differences with distance in mean exchangeable NO_3–N were observed in the above samples *(Table 21)*.

SUMMARY AND CONCLUSIONS

The effect of three anaerobic swine lagoons on ground water quality was investigated in the Coastal Plain region of Virginia. The lagoons under study were located on soils with high water tables and with varying drainage characteristics. Ground water was sampled in 64 wells located at various depths and distances from the lagoons. These samples were taken monthly from September, 1974, through January, 1975; and bi-monthly thereafter through November, 1975. Biological and chemical analyses were completed to determine the extent of ground water contamination. The biological constituent analyzed was number of fecal coliform bacteria. Chemical constituents determined were concentrations of Cl, Cu, Mn, NH_4—N, NO_3—N, PO_4—P, and Zn.

The lagoon at the VSEC was located on a poorly drained soil with a clayey subsoil. Biological and chemical data indicated either no or slight contamination beyond 3 m from the lagoon. Seepage from the lagoon was probably inhibited by the low hydraulic conductivity of the clay subsoil. The rate of pollutant movement was extremely slow, as is indicated by the low values of NH_4—N at distances greater than 3 m after eight years of lagoon operation. This would be due to effects of the clayey subsoil, of biological sealing, and of a small hydraulic head (difference in effluent level and the water table height) at this site. The construction of the lagoon at ground level may present a contamination problem more due to overflow during wet seasons than to seepage. Many animal burrows were observed in this area, and these may have caused channeling from the lagoon. The isolated nature of the VSEC and the low concentrations of pollutants found in the ground water samples indicate that this lagoon does not pose a threat to the ground water supply of the area.

The lagoon at the TRACEC is located on a somewhat poorly to poorly drained soil with a sandy clay loam subsoil. This lagoon was built partly above ground level. Seepage from the lagoon embankment was demonstrated by high Cl and NO_3—N concentrations in ground water samples from perforated wells. This seepage was probably due to destruction of the biological seal in the embankment during drying.

Construction of a lagoon above ground level rather than at ground level increases the distance between the effluent height and the water table and, thereby, results in a greater hydraulic head. Seepage may be greater from the lagoon at the TRACEC than at the VSEC because of a greater hydraulic head and a higher hydraulic conductivity of the sandy clay loam subsoil. Movement of pollutants in ground water would be expected to be less inhibited by sandy clay loam subsoil than by clay subsoil. The greater hydraulic conductivity and assumed lower cation sorption would allow contamination to move at a faster rate and at a farther distance from the TRACEC than the VSEC lagoon.

The ground water quality was affected beyond 16.8 m, but reached background levels 36.6 m from the TRACEC lagoon site. Although contamination of ground water was evident at this site, the concentrations of pollutants did not exceed USPHS drinking water standards beyond 3 m from the lagoon. Therefore, it can be concluded that this lagoon is not an immediate threat to ground water supplies in the area.

The lagoon located at the private farm was built partly above ground level on a moderately to poorly drained area with a sandy subsoil. Biological sealing was depended upon for prevention of seepage from the lagoon. Pollutants entering ground water would probably move more rapidly in sandy subsoils than in either sandy clay or clay subsoils. This would partially explain the higher amount of ground water contamination around the lagoon at the private farm than those at the TRACEC and VSEC.

One well series at the private farm was located on a moderately well-drained area, and the other on a poorly drained area. Relatively high NO_3—N concentrations were found in ground water sampled from the moderately well-drained area, whereas NO_3—N concentrations in the poorly drained area dropped rapidly beyond the embankment of the lagoon. These results and Cl concentrations in the ground water indicated seepage from the lagoon. The higher NO_3—N concentrations in the moderately well-drained area may reflect a greater rate of nitrification.

Other sources besides seepage from the lagoon may have caused the high pollutant concentrations in ground water at the private farm site. These sources may be contamination from effluent application on a nearby field and from lagoon effluent overflow. On many occasions, concentrations of NO_3—N and Cl in ground water from this site exceeded USPHS drinking water standards. It can be concluded that wells for drinking water from shallow aquifers should be avoided in this area, and that deeper wells should be monitored for contamination from leaching.

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TABLES

TABLE 1

Mean Concentrations of NH_4-H in Groundwater at Various Depths and Distances from the Anaerobic Swine Lagoon Located at the VSEC

Distance from lagoon	Well depth, m		
	3	4.6	6
m	ppm NH_4-N		
3	10.8a*	0.1a	4.1a
15	0.5b	0.2a	0.1b
30	0.1b	0.1a	0.1b

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 2

Mean Cl Concentrations in Groundwater Sampled From the SE and NW Well Sets Located at the VSEC Lagoon Site

Distance from lagoon	Well depth, m					
	Southeast			Northwest		
	3	4.6	6	3	4.6	6
m	ppm Cl*					
3	60a**	7a	6a	109a	148a	40a
15	8b	6a	13a	97b	75a	47a
30	8b	9a	7a	52b	45b	18b

* Means within columns followed by different letters are significantly different (P<0.05). Location means are significantly different (P<0.05).

** Contaminated well.

TABLE 3

Mean Concentrations of Cl in Groundwater Sampled at the Water Table Surface and at Distances of 3 and 15 m From the Anaerobic Swine Lagoon Located at the VSEC

Distance from lagoon	Well set	
	Southeast	Northwest
m	ppm Cl*	
3	80a	90a
15	10b	19b

* Means within a column followed by different letters are significantly different ($P<0.05$).

TABLE 4

Chloride Concentration in Groundwater Sampled On Four Consecutive Days from the SE Well Set Located at the VSEC Lagoon Site

Sampling Date	Distance from lagoon	Well depth, m		
		3	4.6	6
	m	—— ppm Cl ——		
12/11/73	3	21*	30	12
	15	7	9	7
	30	6	8	8
12/12/73	3	71*	27	8
	15	8	8	7
	30	13	7	8
12/13/73	3	50*	27	8
	15	7	9	7
	30	6	7	8
12/14/73	3	62*	30	4
	15	9	8	8
	30	6	10	15

* Chloride concentrations in groundwater from the contaminated well.

TABLE 5

Mean Cl, NH_4-N, and NO_3-N Concentrations In Groundwater Sampled at Various Depths and Distances From an Anaerobic Swine Lagoon Located at the TRACEC*

Distance from lagoon	Well depths, m								
	3	4.6	6	3	4.6	6	3	4.6	6
m	— ppm NH_4-N* —			— ppm Cl* —			— ppm NO_3-N* —		
3	1.9a	0.1a	0.2a	103a	49a	35a	2.7a	0.6a	0.7a
15	0.7a	0.3a	0.2a	33b	33a	20a	0.9b	0.2a	0.2a
Check	0.2a	0.2a	0.1a	6c**	6b**	11b	0.3b	0.6a	2.5b

* Means within a column followed by different letters are significantly different ($P<0.05$).

** Excludes September, 1975 samples.

TABLE 6

Depth to Water Tables in Wells
That Were 3 m, 4.6 m, and 6 m Deep
And That Were Located 15 m
From an Anaerobic Swine Lagoon at the TRACEC

Sampling Date	Well depth, m		
	3	4.6	6
	cm		
12/18/74	86	155	150
1/3/75	91	152	152
1/8/75	86	145	140
1/22/75	81	127	127
1/29/75	69	119	119
2/5/75	53	124	119
2/12/75	61	124	122
2/19/75	46	117	112
2/26/75	58	123	119
3/5/75	69	130	130
3/12/75	56	140	142

TABLE 7
Depth to Water Tables at the Check Wells
At the TRACEC Lagoon Site

Sampling Date	Well depth, m		
	3	4.6	6
	cm		
12/18/74	117	117	190
1/3/75	119	119	168
1/8/75	119	94	155
1/22/75	76	72	150
1/29/75	86	86	135
2/5/75	41	41	137
2/12/75	89	91	142
2/19/75	51	56	139
2/26/75	84	84	137
3/5/75	97	66	150
3/12/75	104	107	163

TABLE 8
Mean Cl Concentrations
In Groundwater Sampled from Temporary Wells
Around the Lagoon at the TRACEC

Distance from lagoon	Location around lagoon		
	Front	Back	Side
m	ppm Cl*		
3	111a	10a	38a
15	23b	8a	27a

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 9
Concentrations of NO_3-N, NH_4-N, and Cl
From Perforated Wells Located at Various Distances
From the Lagoon at the TRACEC

Distance from lagoon	Ion under study		
	NO_3-N	NH_4-N	Cl
m	ppm		
0.0	13.3	18.8	264
0.8	30.7	3.5	168
1.5	3.9	0.7	160
2.3	0.9	1.1	155
3.0	1.2	0.6	153
3.8	0.8	0.3	79
4.6	1.2	0.5	180
6.1	1.0	0.5	117
7.6	1.2	0.6	103
10.7	1.4	0.7	90
13.7	0.6	3.4	63
16.8	0.8	0.6	67
22.9	<0.2	0.2	53
29.0	<0.2	0.2	33
36.6	4.1	0.3	12

TABLE 10

Exchangeable NH_4-N in Soil Sampled at Various Depths And Distances from an Anaerobic Swine Lagoon Located at the TRACEC

Distance from lagoon	Depth, cm				
	30-60	60-90	90-120	120-150	150-180
m	ppm NH_4-N*				
3	6.3a	6.9a	11.9b	7.3a	1.5a
15	9.8a	6.2a	2.1a	3.0a	0.2a

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 11

Exchangeable NO_3-N in Soil Sampled at Various Depths and Distances From an Anaerobic Swine Lagoon Located at the TRACEC

Distance from lagoon	Depth, cm				
	30-60	60-90	90-120	120-150	150-180
m	ppm NO_3-N*				
3	<0.2	<0.2	0.8	0.4	0.2
15	<0.2	<0.2	<0:2	0.1	<0.2

* Means within columns were not significantly different ($P<0.05$).

TABLE 12

Mean NH_4-N Concentrations in Groundwater Sampled At Various Depths and Distances from an Anaerobic Swine Lagoon Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Well depth, m					
	Series I			Series II		
	3	4.6	6	3	4.6	6
m	ppm NH_4-N*					
3	357.9a	12.5a	40.9a	0.4a	0.1a	0.1a
15	25.4b	63.4a	97.6a	0.1a	0.2a	0.2a
30	16.0b	64.0a	0.3b	0.2a	0.1a	0.2a

* Means within columns followed by different letters are significantly different ($P<0.05$). Location means are significantly different ($P<0.05$).

TABLE 13

Mean Concentrations of Cl in Groundwater Sampled At Various Depths and Distances from an Anaerobic Swine Lagoon Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Well depth, m					
	Series I			Series II		
	3	4.6	6	3	4.6	6
m	ppm Cl*					
3	272a	119a	166a	12b	15a	25a
15	162b	114a	183a	10b	28a	14a
30	153b	72a	92a	103a	7a	9a

* Means within columns followed by different letters are significantly different ($P<0.05$). Location means are significantly different ($P<0.05$).

TABLE 14
Concentrations of NH_4-N, NO_3-N, and Cl
In Groundwater Sampled from Perforated Wells
Located in Series I at the Private Farm Lagoon Site

Distance from lagoon	Ion under study		
	NH_4-N	NO_3-N	Cl
m	ppm		
0.0	51.3	49.3	256
0.8	12.3	68.1	93
1.5	63.8	66.7	62
2.3	15.9	41.6	23
3.0	8.9	35.5	8
3.8	76.3	4.2	49
4.6	10.6	0.4	4
6.1	20.7	0.2	29
7.6	18.0	<0.2	51
10.7	13.5	<0.2	49
13.7	20.8	<0.2	103
16.8	19.5	<0.2	204
22.9	18.0	<0.2	49
29.0	0.5	4.0	60
36.6	0.4	0.5	6

TABLE 15

Mean Concentrations of NO_3-N in Groundwater Sampled At Various Depths and Distances from an Anaerobic Swine Lagoon Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Well depth, m					
	Series I			Series II		
	3	4.6	6	3	4.6	6
m	ppm NO_3-N*					
3	3.2a*	0.2c**	0.2b	9.5a	10.7a	1.0b
15	0.2a	11.2b**	6.3a	2.9b	4.8b	5.0a
30	1.6a	17.2a**	0.2b	3.2b	2.8c	6.0a

* Means within columns followed by different letters are significantly different ($P<0.05$).

** Series means at the same depth and distance that are significantly different ($P<0.05$)

TABLE 16

Mean Cl Concentrations in Groundwater Sampled From Temporary Wells at 3 m, 15 m, and 34 m From the Lagoon Located at a Private Farm In Suffolk, Virginia

Distance from lagoon	Location	
	Series I	Series II
m	ppm Cl*	
3	45a	23a
15	18b	14a
34	2c	--**

* Means within columns followed by different letters are significantly different ($P<0.05$).

** A sample was not taken beyond 15 m from the lagoon.

TABLE 17

Mean Exchangeable NO_3-N in Soil
At Various Depths and Distances in Series I
Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Depth, cm			
	30-60	60-90	90-120	120-150
m	ppm NO_3-N*			
3	0.3a	2.7a	1.7a	7.9b
15	1.2a	0.5a	0.2a	1.0a
34	<0.2a	0.4a	0.3a	1.7a

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 18

Mean Exchangeable NH_4-N in Soil
At Various Depths and Distances in Series I
Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Depth, cm			
	30-60	60-90	90-120	120-150
m	ppm NH_4-N*			
3	10.6a	2.0a	3.4a	1.9a
15	6.7a	2.4a	7.2a	1.8a
34	2.1b	1.9a	2.7a	1.7a

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 19

Concentrations of NH_4-N, NO_3-N, and Cl in Groundwater Sampled From Perforated Wells in Series II Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Ion under study		
	NH_4-N	NO_3-N	Cl
m	ppm		
0.0	45.3	66.9	123
0.8	65.1	100.8	118
1.5	7.5	90.5	54
2.3	3.7	68.8	37
3.0	1.5	23.9	15
3.8	0.9	9.3	27
4.6	0.6	15.9	23
6.1	0.3	8.6	13
7.6	0.2	5.4	10
10.7	0.3	7.7	18
13.7	0.2	5.1	35
16.8	0.2	1.9	15
22.9	0.2	3.8	8
29.0	0.1	1.8	5
36.6	0.4	0.5	7

TABLE 20

Mean Exchangeable NH_4-N in Soil
At Various Depths and Distances in Series II
Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Depth, cm			
	30-60	60-90	90-120	120-150
m	ppm NH_4-N*			
3	2.6a	2.0a	2.3a	1.2a
15	1.4a	3.4a	1.4a	5.0b

* Means within columns followed by different letters are significantly different ($P<0.05$).

TABLE 21
Mean Exchangeable NO_3-N in Soil
At Various Depths and Distances in Series II
Located on a Private Farm in Suffolk, Virginia

Distance from lagoon	Depth, cm			
	30-60	60-90	90-120	120-150
m	ppm NO_3-N*			
3	4.3	3.2	5.2	6.1
15	2.3	<0.2	4.9	3.0

* Means in columns were not significantly different ($P<0.05$).

FIGURES

FIGURE 1

Well Placement Around an Anaerobic Swine Lagoon Located at the Virginia Swine Evaluation Center

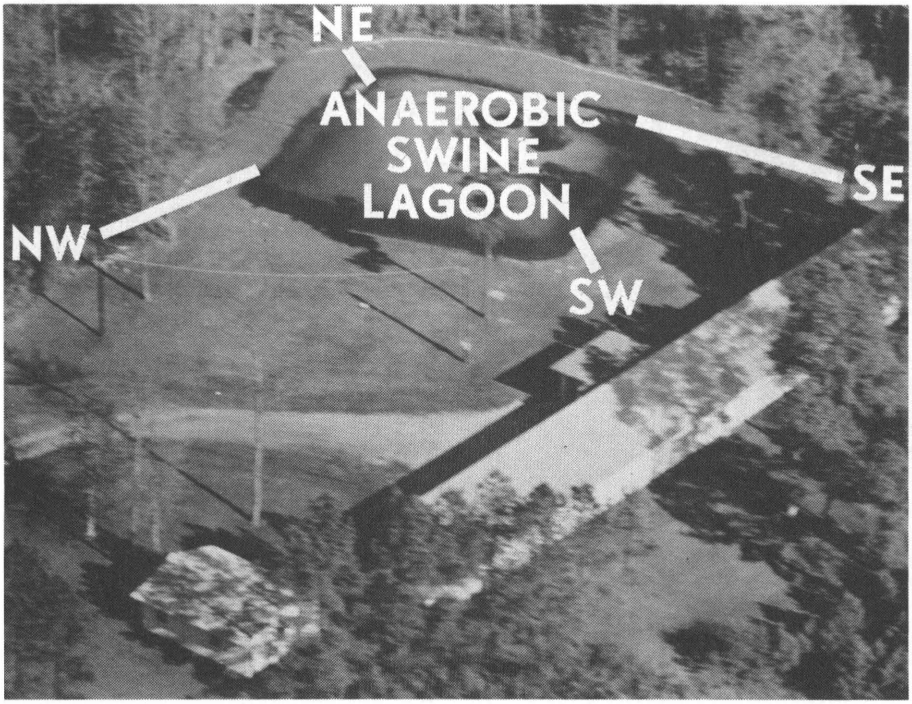


FIGURE 2
Well Placement Around an Anaerobic Swine Lagoon
Located at the Tidewater Research and Continuing Education Center

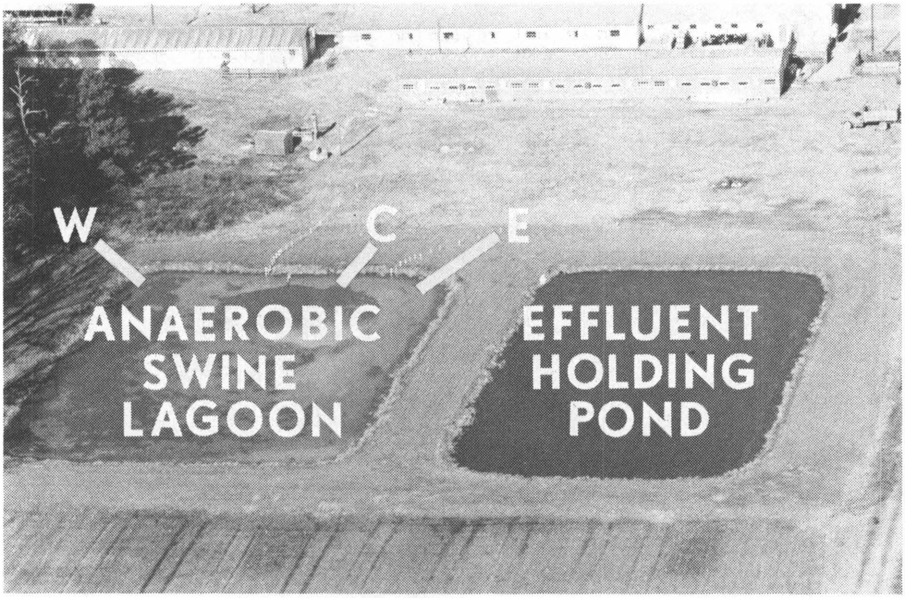


FIGURE 3
Well Placement Around an Anaerobic Swine Lagoon
Located at the Private Farm

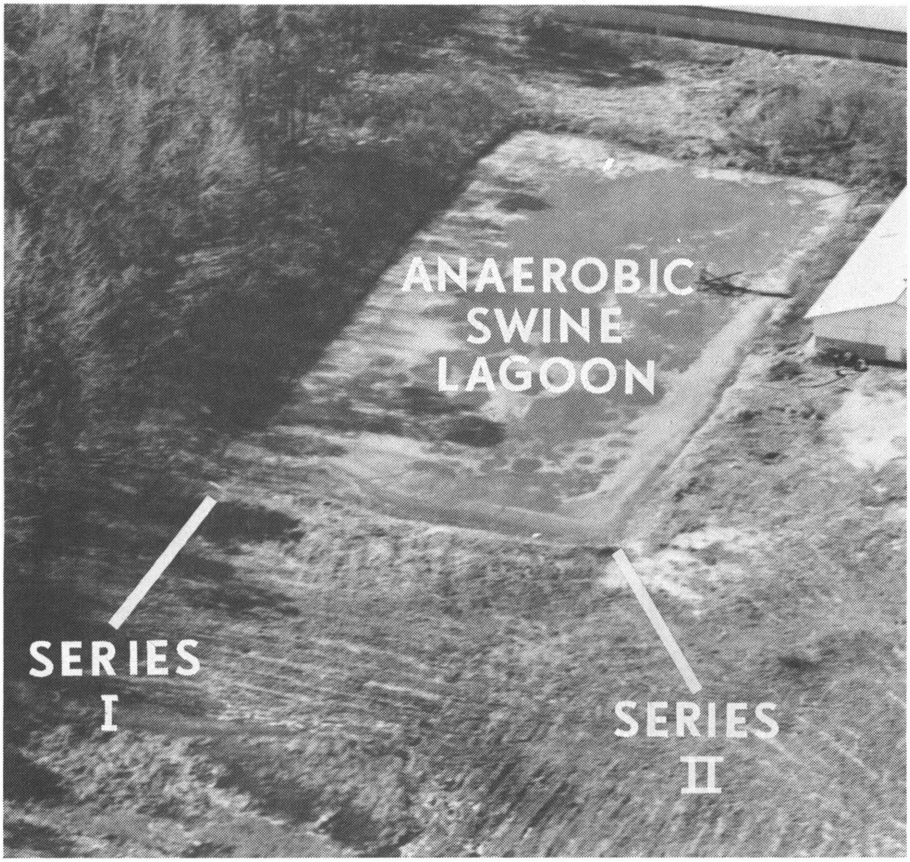


FIGURE 4
Test Well and Sampling System

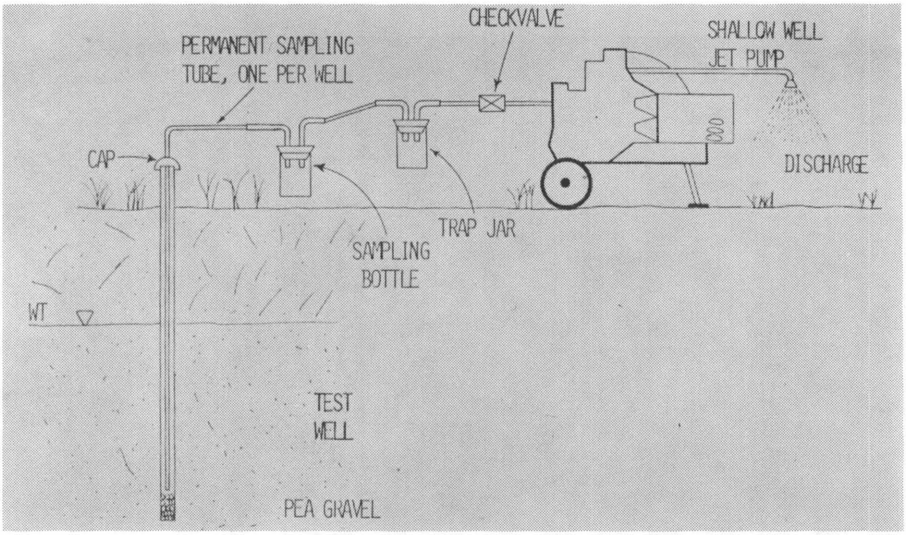


FIGURE 5
Piezometric Map of the Virginia Swine Evaluation Center Lagoon Site

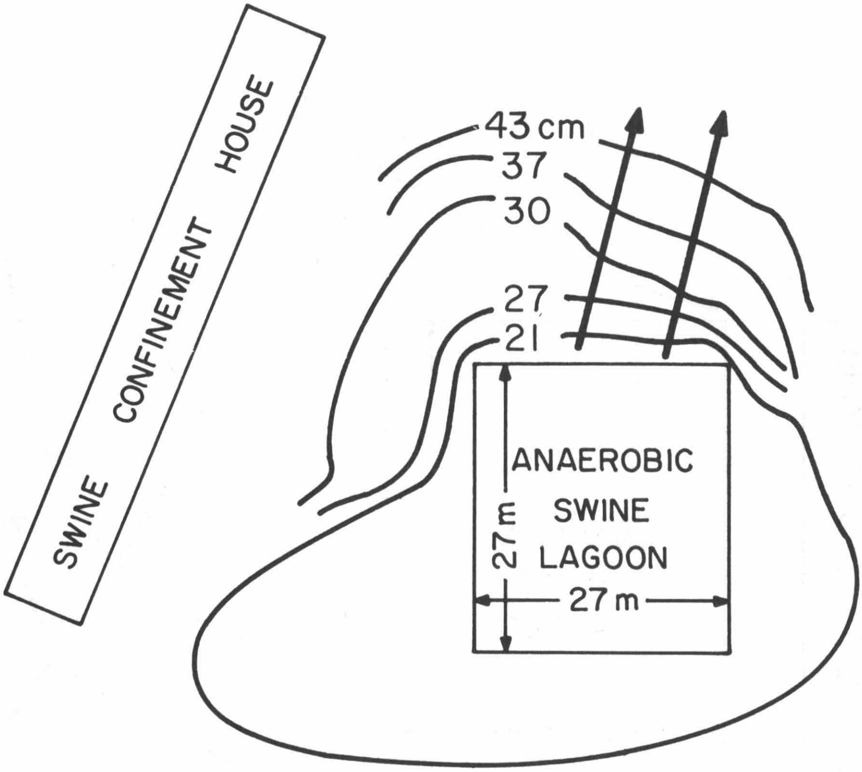


FIGURE 6

Piezometric Map of the Tidewater Research and Continuing Education Center Lagoon Site

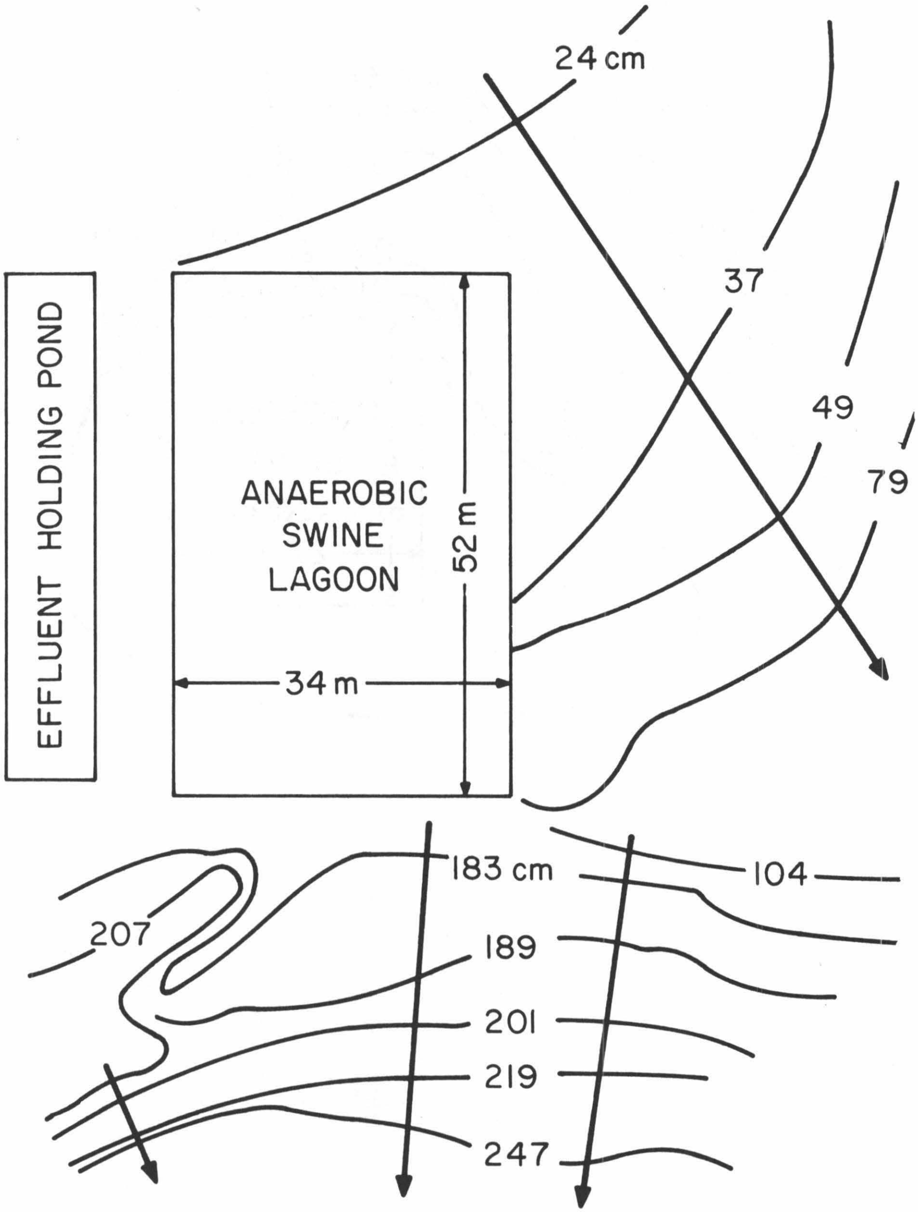
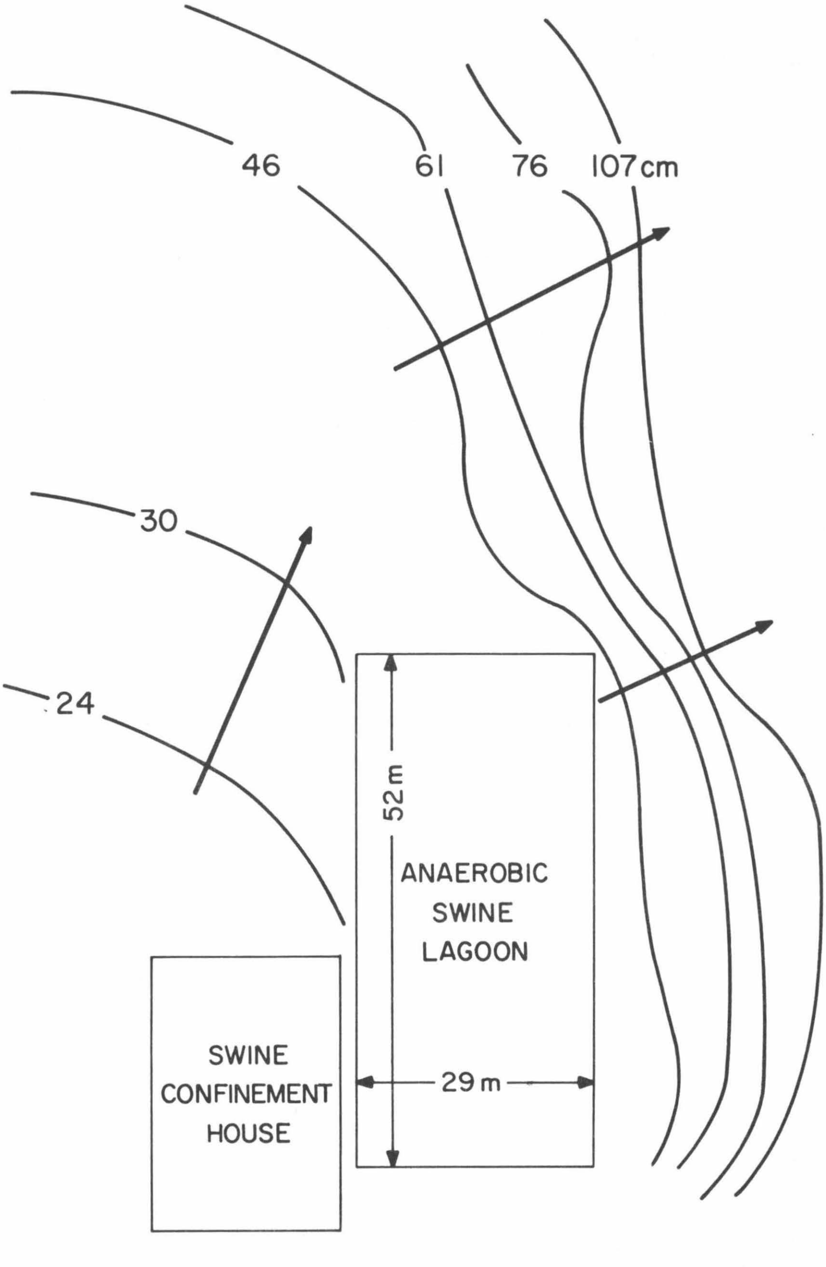


FIGURE 7
Piezometric Map of the Private Farm Lagoon Site



The Virginia Water Resources Research Center is a federal-state partnership agency attempting to find solutions to the state's water resource problems through careful research and analysis. Established at Virginia Polytechnic Institute and State University under provisions of the Water Resources Research Act of 1964 (P.L. 88-379), the Center serves five primary functions:

- It studies the state's water and related land-use problems, including their ecological, political, economic, institutional, legal, and social implications.
- It sponsors and administers research investigations of these problems.
- It collects and disseminates information about water resources and water resources research.
- It provides training opportunities in research for future water scientists enrolled at the state's colleges and universities.
- It provides other public services to the state in a wide variety of forms.

More information on programs and activities may be obtained by contacting the Center at the address below.

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