Research on Infiltration and Leakage from Lagoons & Ponds

Compiled by Jean Mendoza, 2014

Baram, S., Arnon, S., Ronen, Z., Kurtzman, D. & Dahan, O. (2012) Infiltration mechanism controls nitrification and denitrification processes under dairy waste lagoon. Journal of Environmental Quality. 41: 1623 – 1632. doi:10.2134/jeq2012.0015. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/41/5/1623?access=0&view=pdf and http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

Barrington, S.F. & Broughton, R.S. (1988) Designing earthen storage facilities for manure. Agricultural Engineering Dept. McGill University. Canadian Agricultural Engineering. 289-292.Retrieved from http://www.csbe-scgab.ca/docs/journal/30/30_2_289_raw.pdf

Barrington, S.F. & Madramootoo, C.A. (1989) Investigating Seal formation from manure infiltration into soils. Transactions of the ASABE. 32 (3): 0851-0856. Abstract retrieved from http://elibrary.asabe.org/abstract.asp?aid=31081&t=2&redir=&redirType=

Cihan, A., Tyner, J.S., & Wright, W.C. (2006) Seal formation beneath animal waste holding ponds. Trans. ASAE 49:1539 – 1544. Retrieved from http://www.prairieswine.com/pdf/3110.pdf

Ciravolo, T.G., Martens, D.C., Hallock, D.L., Collins, E.R., Kornegay, E.T., & Thomas, H.R. (1979) Pollutant movement to shallow groundwater tables from anaerobic swine wastes lagoons. Journal of Environmental Quality 8: 126 – 130. Abstract retrieved from https://www.agronomy.org/publications/jeq/abstracts/8/1/JEQ0080010126?access=0&view=pdf

Copeland, C. & Zinn, J. (1998) Animal waste management and the environment: background for current issues. CRS Report for Congress. Retrieved from http://www.cnie.org/nle/crsreports/Agriculture/ag-48.cfm plus http://www.cnie.org/nle/crsreports/Agriculture/ag-48c.cfm

Culley, J.L.B., & Phillips, P.A. (1982) Sealing of soils by liquid cattle manure. Canadian Agricultural Engineering. 24: 87 -89. Retrieved from http://www.csbe-scgab.ca/docs/journal/24/24_2_87_ocr.pdf

DeSutter, T.M., Pierzynski, G.M. & Hamm, J.M. (2005) Movement of lagoon-liquor constituents below four animal-waste lagoons. Journal of Environmental Quality. 34: 1234-1242. doi:10.2134/jeq2004.0296. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/34/4/1234?access=0&view=pdf and http://soilcrop.colostate.edu/ham/pdf_files/DeSutterPierzynskiHam2005.pdf

Domansky, J. (2012) Infiltration and water quality impacts associated with wastewater ponds. Texas Digital Library. Retrieved from http://repositories.tdl.org/tdl-ir/handle/2346/9813

Erickson, D. (1992) Summary of Dairy Lagoon Groundwater Assessments. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e26.pdf

Erickson, D. (1992) Groundwater Quality Assessment Hornby Lagoon Sunnyside Washington. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e23.pdf

Erickson, D. (1992) Groundwater Quality Assessment – Sheridan Dairy Lagoon, Adna, Washington. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e24.pdf

Erickson, D. (1992) Groundwater Quality Assessment – Whatcom County Dairy Lagoon #2, Lynden, WA. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e25.pdf

Erickson, D. (1992) Edaleen Dairy Lagoon Groundwater Quality Assessment. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/91e11.pdf

Esser, B. K., Beller, H.R., Carle, S.F., Hudson, G.B., Kane, S.R., Leif, R.N., LeTain, T.E., McNab, W.N. & Moran, J.E. (2009) California GAMA Program: Impact of Dairy Operations on Groundwater Quality. California State water Resources Control Board. Retrieved from http://www.waterboards.ca.gov/gama/docs/ucrl_tr_223509_gamawwfinal_report.pdf

García, A. R., Maisonnave, R. Massobrio, M.J., & Fabrizio de Lorio, A. R. (2011) Field-Scale Evaluation of Water Fluxes and Manure Solution Leaching in Feedlot Pen Soils. Journal of Environmental Quality. 41: 1591–1599 doi:10.2134/jeq2011.0320. Abstract retrieved from https://www.agronomy.org/publications/jeq/abstracts/41/5/1591

Glanville, T.D., Baker J.L., Melvin, S.W., & Agua, M.M. (2001) Measurement of leakage from earthen manure structures in Iowa. Transactions of the ASAE 44(6): 1609-1666. Retrieved from http://www.prairieswine.com/pdf/3024.pdf

Gooddy, D.C., Clay, J.W., & Bottrell, S.H. (2002) Redox-driven changes in pore water chemistry in the unsaturated zone of the chalk aquifer beneath unlined cattle slurry lagoons. Applied Geochemistry. 17: 903 – 921. doi: 10.1016/S0883-2927(2)00055-0. Abstract retrieved from http://www.sciencedirect.com/science/article/pii/S0883292702000550

Gooddy, D.C., Hughes, A.G., Williams, A.T., Armstrong, A.C., Nicholson, R.J. & Williams, J.R. (2001) Field and modeling studies to assess the risk to UK groundwater from earth-based stores for livestock manure. Soil Use Management. 17: 128 – 137. doi: 10.1111/j.1475 – 2743.2001.tb00018x. Retrieved from http://nora.nerc.ac.uk/7770/2/Manuscript_F%26M_Studies.pdf

Gooddy, D.C., Withers, P.J.A., McDonald, H.G. & Chilton, P.J. (1998) Behavior and impact of cow slurry beneath a storage lagoon: II. Chemical composition of chalk porewater after 18 years. Water Air Soil Pollution. 107: 51 – 72. doi: 10.1023/A:1004975615804. Retrieved from http://link.springer.com/article/10.1023%2FA%3A1004975615804?LI=true#page-1 and http://nora.nerc.ac.uk/7768/ (See Withers et al, 1998)

Ham, J.M. & DeSutter, T.M. (1999a) Seepage Losses and Nitrogen Export from Swine-Waste Lagoons: A Water Balance Study. Journal of Environmental Quality 28(4): 1090 – 1099. Abstract retrieved from https://www.soils.org/publications/jeq/abstracts/28/4/JEQ0280041090?access=0&view=pdf

Ham, J.M. (1999b) Measuring evaporation rates and seepage losses from lagoons used to contain animal waste. Transactions of the ASAE 42(5): 1303 – 1312. Retrieved from http://www.soilcrop.colostate.edu/ham/pdf_files/ham1999.pdf

Ham, J.M. (2002) Seepage losses from animal waste lagoons: A summary of a four year investigation in Kansas. Trans. ASAE 45: 983 – 992. Retrieved from http://www.prairieswine.com/pdf/3034.pdf

Ham, J. M., & Baum, K.A. (2009) Measuring seepage from waste lagoons and earthen basins with an overnight water balance test. Trans ASAE 53: 835 – 844. Retrieved from http://soilcrop.colostate.edu/ham/pdf_files/Ham_Baum_2009.pdf

Ham, J.M., & DeSutter, T.M. (2000) Toward site-specific design standards for animal-waster lagoons: Protecting ground water quality. Journal of Environmental Quality. 29: 1721 – 1732. doi: 10.2134/jeq2000.00472425002900060001x. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/29/6/JEQ0290061721?access=0&view=pdf and http://state-cafos.org/docs/HamDeSutter2000.pdf

Ham, J.M., Reddi, L.M. & Rice, C.W. (1999) Animal waste water quality study. Kansas State University and the Kansas Water Office. Retrieved from http://www.ksre.ksu.edu/bookstore/pubs/LAGOON.pdf

Harter, T., Davis, H., Mathews, M.C. & Meyer, R.D. (2002) Shallow groundwater quality on dairy farms with irrigated forage crops. Journal of Contamination Hydrology. 55: 287 – 315. doi: 10.1016/S0169-7722(01)00189-9. Abstract retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11999633

Huffman, R.L. (2004) Seepage evaluation of older swine lagoons in North Carolina. Transactions of the ASAE. 47(5): 1507−1512. Retrieved from http://www.prairieswine.com/pdf/3112.pdf

Jones, D.D., Koelsch, R.K., Mukhtar, S., Sheffield, R. & Worley, J.W. (2006) Closure of earthen manure structures (Including basins, holding ponds and lagoons). Conference Presentations and White Papers. Biological Systems Engineering. Retrieved from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1003&context=biosysengpres&sei-redir=1&referer=http%3A%2F%2Fscholar.google.com%2Fscholar%3Fq%3DInfluence%2Bof%2Bseal%2Band%2Bliner%2Bhydraulic%2Bproperties%2Bon%2Bthe%2Bseepage%2Brate%2Bfrom%2Banimal%2Bwaste%2Bholding%2Bponds%2Band%2Blagoons%26btnG%3D%26hl%3Den%26as_sdt%3D0%252C48%26as_vis%3D1#search=%22Influence%20seal%20liner%20hydraulic%20properties%20seepage%20rate%20from%20animal%20waste%20holding%20ponds%20lagoons%22

Korom, S.F. & Jeppson, R.W. (1994) Nitrate contamination from dairy lagoons constructed in coarse alluvial deposits. Journal of Environmental Quality. 23: 973 – 976. doi: 10.2134/jeq1994.00472425002300050018x. Abstract retrieved from https://www.crops.org/publications/jeq/abstracts/23/5/JEQ0230050973?access=0&view=pdf and https://www.agronomy.org/publications/jeq/abstracts/23/5/JEQ0230050973

Libra, R.L., Quade, D.J. & Seigley, L.S. (n.d.) Groundwater monitoring at earthen manure-storage structures in Iowa. Iowa Dept. of Natural Resources. Retrieved from http://www.igsb.uiowa.edu/Mapping/kirkwood/kirkwood.htm

McCurdy, M. & McSweeney, K. (1993) The origin and identification of macropores in an earthen=lined manure storage basin. Journal of Environmental Quality. 22(1): 148 – 154. Abstract retrieved from https://www.soils.org/publications/jeq/abstracts/22/1/JEQ0220010148?access=0&view=pdf

McNab, W.W., Singleton, M.J., Moran, J.E. & Esser, B.K. (2006) Assessing the impact of animal waste lagoon seepage on the geochemistry of an underlying shallow aquifer. Environmental Science and Technology. Retrieved from https://e-reports-ext.llnl.gov/pdf/331439.pdf

Meyer, J.L., Olson, E., & Baier, D. (1972) Manure holding ponds found self-sealing. California Agriculture. 26: 14 – 15. Retrieved from http://ucce.ucdavis.edu/files/repositoryfiles/ca2605p14-69365.pdf

Miller, M.H., Robinson, J.B., & Gillham, R.W. (1985) Self-sealing of earthen liquid manure storage ponds. 1. A case-study. Journal of Environmental Quality. 14: 533 – 538. doi: 10.2134/jeq1985.00472425001400040013x. Abstract retrieved from https://www.agronomy.org/publications/jeq/abstracts/14/4/JEQ0140040533 and https://www.crops.org/publications/jeq/abstracts/14/4/JEQ0140040533?access=0&view=pdf

Miller, M. H., J. B. Robinson, and D. W. Gallagher. "Accumulation of Nutrients in Soil Beneath Hog Manure Lagoons." Journal of Environmental Quality 5 (3): 279-82. Abstract Retrieved from http://www.pork.org/ResearchDetail/1073/AccumulationofNutrie.aspx#.UWCUecpXr5Q

Nolan, B. T., B. C. Ruddy, K. J. Hitt, and D. R. Helsel. 1997. Risk of nitrate in groundwaters of the United States-A national perspective. Environ. Sci. Technol. 31:2229-2236. Retrieved from http://water.usgs.gov/nawqa/nutrients/pubs/est_v31_no8/est_v31_no8.pdf

North Carolina Division of Water Quality (1998) Impact of Animal Waste Lagoons on Groundwater Quality. Retrieved from http://portal.ncdenr.org/c/document_library/get_file?uuid=51d2c023-99c3-47c9-a8fb-834bfcd14c6f&groupId=38364

Nunez-Delgado, A., Lopez-Periago, E., Diaz-Fierro-Viquiera, F. (2002) Pollution attenuation by soils receiving cattle slurry after passage of a slurry-like feed solution.: Column experiments. Bioresource Technology 84(3): 229 – 236. Abstract Retrieved from http://www.sciencedirect.com.ezp.waldenulibrary.org/science/article/pii/S0960852402000500

Oliver, J.C. & Meyer, J.L. (1974) Subfloor monitoring of Shady Grove dairy liquid manure holding pond. California Agriculture, 28: 6-7. Retrieved from http://ucce.ucdavis.edu/files/repositoryfiles/ca2804p6-64108.pdf

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999a) Modeling seepage from an unlined beef cattle feedlot runoff storage pond. Trans. ASAE 42: 1437 – 1445. Abstract retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=1353660

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999b) Seepage characteristics and hydraulic properties of a feedlot runoff storage pond. Trans ASAE 42: 369 – 380. Retrieved from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1179&context=biosysengfacpub&sei-redir=1&referer=http%3A%2F%2Fscholar.google.com%2Fscholar%3Fq%3DSeepage%2Bcharacteristics%2Band%2Bhydraulic%2Bproperties%2Bof%2Ba%2Bfeedlot%2Brunoff%2Bstorage%2Bpond%26btnG%3D%26hl%3Den%26as_sdt%3D0%252C48%26as_vis%3D1#search=%22Seepage%20characteristics%20hydraulic%20properties%20feedlot%20runoff%20storage%20pond%22

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999c) Seepage from earthen animal waste ponds and lagoons – An overview of research results and state regulations. Trans. ASAE 42: 485 – 493. Abstract retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=1240129

Parker, D.B., Rogers, W.J., McCullough, M.C., Cahoon, J.E., Rhoades, M.B. & Robinson, C. (2001). Infiltration characteristics of cracked clay soils in bottoms of feed yard playa catchments. Paper presented at: ASAE Annual International Meeting, Sacramento, CA. 29 July – 1 August, 2001. Paper 01-2281. Abstract retrieved from http://elibrary.asabe.org/abstract.asp?aid=3520&t=2&redir=aid=3520&redir=[confid=sca2001]&redirType=techpapers.asp&redirType=techpapers.asp

Quade, D.J., Libra, R.D., & Siegley, L.S. (n.d.) Groundwater monitoring at an earthen manure-storage structure. Iowa Dept. of Natural Resources. Retrieved from http://www.igsb.uiowa.edu/Mapping/EMS/EMSGroundMon.htm

Reddi, L. and Davalos, H. (2000). Animal Waste Containment in Anaerobic Lagoons Lined with Compacted Clays. *Journal of Geotech. Geoenviron. Eng.*, 126(3), 257–264. Retrieved from http://ascelibrary.org/doi/abs/10.1061/(ASCE)1090-0241(2000)126:3(257) and http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CDsQFjAB&url=http%3A%2F%2Fwww.kcare.ksu.edu%2FDesktopModules%2FViewDocument.aspx%3FDocumentID%3D3277&ei=tqFfUebxCuWgiALzwICYDg&usg=AFQjCNH2vsarVU11FbIBbXlQXkE9-v8hwQ&sig2=yzMCcAErUwXooN_KApzSAA&bvm=bv.44770516,d.cGE

Ritter, W.F. & Chirnside, A.E.M. (1990) Impact of animal waste lagoons on ground-water quality. Biological Wastes 34(1): 39-54. doi.org/10.1016/0269-7483(90)90142-F. Abstract retrieved from http://www.sciencedirect.com/science/article/pii/026974839090142F

Rowsell, J.G., Miller, M.H. & Groenevelt, P.H. (1985) Self-sealing of earthen liquid manure storage ponds. 2. Rate and mechanisms of sealing. Journal of Environmental Quality. 14: 539 – 543. doi:10.2134/jeq1985.00472425001400040014x. Abstract retrieved from https://www.soils.org/publications/jeq/abstracts/14/4/JEQ0140040539?access=0&view=pdf

Sher, Y., Baram, S., Dahan, O., Ronen, Z. & Nejidat, A. (2012). Ammonia transformations and abundance of ammonia oxidizers in a clay soil underlying a manure pond. Federation of European Microbiological Societies. Microbiological Ecology. 81(1): 145 – 155. doi: 10.1111/j.1574-6941.2012.01347.x. Abstract retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.1574-6941.2012.01347.x/abstract

Simpkins, W.W. & Burkart, M.R. (2002) Hydrogeologic settings of earthen waste storage structures associated with confined animal feeding operations in Iowa. Proceedings – Waster Technology. Retrieved from http://www.engg.ksu.edu/HSRC/ag/2002/proceed/b02.pdf

Singleton, M.J., Esser, B.K., Moran, J.E., Hudson, G.B., McNab, W.W. & Harter, T. (2007). Saturated zone denitrification: Potential for natural attenuation of nitrate contamination in shallow groundwater under dairy operations. Environmental Science Technology. 41:759-765. doi: 10.1021/es061253g. Abstract retrieved from http://pubs.acs.org/doi/abs/10.1021/es061253g

Sweeten, J.M. (1998) Cattle feedlot manure and waste water management practices. Retrieved from http://books.google.com/books?hl=en&lr=&id=sL3e09_DWDUC&oi=fnd&pg=PA125&dq=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&ots=1bjx52o7o9&sig=2QNhS9xUiGF2M3a5VWKl1Snk74o#v=onepage&q&f=false

Tyner, J.S., & Lee, J. (2004) Influence of seal and liner hydraulic properties on the seepage rate from animal waste holding ponds and lagoons. Trans. ASAE 47:1739 – 1745. Retrieved from http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

Tyner, J.S., Wright, W.C., & Lee, J. (2006) Lagoon sealing and filter cakes. Trans. ASAE 49:527 – 531. Retrieved from http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

Van der Schans, M.L., Harter, T., Leijnse, A., Mathews, M.C., & Meyer, R.D. (2009) Characterizing sources of nitrate leaching from an irrigated dairy farm in Merced County, California. Journal of Contaminant Hydrology. 110(1-2): 9 - 21. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169772209000862 and http://ucanr.org/sites/groundwater/files/136324.pdf

Westerman, P.W., Huffman, J.S., & Feng, J.S. (1995) Swine lagoon seepage in sandy soil. Transactions of the ASABE. 38(6): 1749-1760. Abstract retrieved from https://elibrary.asabe.org/abstract.asp?aid=28002&t=2&redir=&redirType=

White, I. & Denmead, O.T. (1989) Point and whole basin estimates of seepage and evaporation losses from a saline groundwater-disposal basin. Hydrology and Water Resources Symposium 1989: Comparisons in Australian Hydrology: Preprints of papers. Abstract retrieved from http://search.informit.com.au/documentSummary;dn=484307596156300;res=IELENG

Withers, P.J.A., McDonald, H.G., Smith, K.A., & Chumbley, C.G. (1998). Behavior and impact of cow slurry beneath a storage lagoon: I. 49. doi:10.1023/A:1004923631734. Retrieved from http://link.springer.com/article/10.1023%2FA%3A1004923631734?LI=true#page-1 (See Gooddy et al, 1998)

Abstracts for the Research

Baram, S., Arnon, S., Ronen, Z., Kurtzman, D. & Dahan, O. (2012) Infiltration mechanism controls nitrification and denitrification processes under dairy waste lagoon. Journal of Environmental Quality. 41: 1623 – 1632. doi:10.2134/jeq2012.0015. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/41/5/1623?access=0&view=pdf and http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

Abstract: *Earthen waste lagoons are commonly used to store liquid wastes from concentrated animal feeding operations. The fate of ammonium (NH_4^+) and nitrate (NO_3^-) was studied in the vadose zone below earthen-clay dairy farm waste lagoons using three independent vadose zone monitoring systems. The vadose zone was monitored from 0.5 to 30 m below land surface through direct sampling of the sediment porewater and continuous measurement of the sediment profile's water content variations. Four years of monitoring revealed that wastewater infiltration from the lagoon is controlled by two mechanisms: slow (mm d^{-1}), constant infiltration from the lagoon bed; and rapid (m h^{-1}) infiltration of wastewater and rainwater via preferential flow in desiccation cracks formed in the unsaturated clay sediment surrounding the lagoon banks. The preferential flow mechanism is active mainly during wastewater-level fluctuations and intensive rain events. The vadose zone below the waste sources remained unsaturated throughout the monitoring period, and all infiltrating NH_4^+ was oxidized in the upper 0.5 m. The NH_4^+ oxidation (nitrification) was coupled with NO_3^- reduction (denitrification) and depended on the sediment water content, which was controlled by the infiltration mechanism. Coupled nitrification–denitrification (CND) resulted in 90 to 100% reduction in the total nitrogen mass in the vadose zone, with higher removal under high water content (~0.55 m^3 m^{-3}). Mass balance of nitrogen and isotopic composition of NO_3^- indicated that CND, rather than cation exchange capacity, is the key factor regulating nitrogen's fate in the vadose zone underlying earthen waste lagoons.*

Barrington, S.F. & Broughton, R.S. (1988) Designing earthen storage facilities for manure. Agricultural Engineering Dept. McGill University. Canadian Agricultural Engineering. 289-292. Retrieved from http://www.csbe-scgab.ca/docs/journal/30/30_2_289_raw.pdf

Abstract: *Research has recently demonstrated that the sealing of soils by manure occurs mainly through physical mechanisms governed by the geometry and diameter of the soil pores rather than the saturated hydraulic conductivity. In light of such findings, this paper introduces a new approach to the design of earthen manure storage facilities. This new approach requires the soil to meet a maximum equivalent pore size of 2.0 and 0.45 micrograms for the storage of ruminant and monogastric animal manures respectively. A soil's equivalent pore size can be computed from its particle size distribution and porosity. This new approach also requires some groundwater protection for those soils with cation exchange capacities less than 30 meq/100 g even if the soil's equivalent pore size is respected.*

Barrington, S.F. & Madramootoo, C.A. (1989) Investigating Seal formation from manure infiltration into soils. Transactions of the ASABE. 32 (3): 0851-0856. Abstract retrieved from http://elibrary.asabe.org/abstract.asp?aid=31081&t=2&redir=&redirType=

Abstract: *An experiment was conducted to locate and measure the extent of the seal forming as swine manure slurries infiltrate columns of sand and clay loam. The location of the sealing layers was found to vary between soil types. The sand seals developed generally within the surface manure mat while the clay loam seals developed at all of the three locations monitored, namely within the surface manure mat, within the manure soil interface and within the soil itself. The sands demonstrated significantly higher infiltration rates as well as higher seepage COD levels. These higher seepage COD levels indicate the more extensive leaching of manure solids through the sand columns. Thus, the slurry infiltration rate can be related to the extent of manure solid retention at the surface and within the soil. This retention was found to be a function of soil texture rather than soil saturated hydraulic conductivity.*

Cihan, A., Tyner, J.S., & Wright, W.C. (2006) Seal formation beneath animal waste holding ponds. Trans. ASAE 49:1539 – 1544. Retrieved from http://www.prairieswine.com/pdf/3110.pdf

Abstract: *The objectives of this study were to measure the sealing effectiveness of swine and dairy waste applied to a variety of soil textures and to develop a suitable model for describing the sealing process through time. Dairy and swine waste were applied to soil columns packed with sand, silt loam, or clay. A seal developed that reduced the infiltration rates to approximately 10−6 cm s−1 or less within the 54 to 60 day testing period. Throughout the test, the infiltration rates into the clay soil were lowest. Yet as time passed, the differences between soil types diminished. Swine waste applied to sand required more time to develop a seal than all other combinations of waste and soil. A model was developed that describes cumulative infiltration as function of elapsed time, waste height, waste total solids content, and soil hydraulic conductivity. After a stable seal develops, the model predicts that only the seal properties (not the soil properties) are responsible for limiting infiltration. During the seal-dominated phase, a plot of cumulative infiltration versus the square root of time is linear, and the respective slope is dependent on a lumped parameter (Kseal/alpha). A review of available waste infiltration datasets from the literature revealed that Kseal/alpha can be estimated from the total solids concentration of the waste (R2 = 0.87). Predictions of Kseal/alpha were not improved by including the hydraulic conductivity of the soil into the estimate or by analyzing the dairy and swine waste datasets separately. This suggests that neither soil hydraulic conductivity nor waste type greatly affect the infiltration rate during the seal-dominated phase of infiltration.* From https://sites.google.com/site/johnstyner/leakagefromanimalwasteholdingponds

Ciravolo, T.G., Martens, D.C., Hallock, D.L., Collins, E.R., Kornegay, E.T., & Thomas, H.R. (1979) Pollutant movement to shallow groundwater tables from anaerobic swine wastes lagoons. Journal of Environmental Quality 8: 126 – 130. Abstract retrieved from https://www.agronomy.org/publications/jeq/abstracts/8/1/JEQ0080010126?access=0&view=pdf

Abstract: *The effect of three anaerobic swine waste lagoons on ground water quality was investigated in the Atlantic Coastal Plain region. The lagoons studied were located on high-water-table soils with different textures. Ground water was sampled from wells, with unperforated casings, located at depths*

to 6 m and distances to 30 m from the lagoons. These samples were taken monthly from September 1974 through January 1975, and bimonthly thereafter through November 1975. Ground water also was sampled in November 1975 from shallow wells with perforated casings located at distances to 36.6 m from two of the three lagoons. Constituents determined to investigate ground water contamination were density of fecal coliforms and concentrations of Cl, Cu, Mn, NH_4-N, NO_3-N, PO_4-P, and Zn.

Chloride, NH_4-N, and NO_3-N concentrations in ground water samples indicated that seepage entered ground water from each of the three lagoons. Rupture of lagoon seals leading to seepage was attributed to drying of exposed subsoil or embankment soil during recession of lagoon liquid levels and to gas release from microbial activity in soil beneath the seal. Overall, a low level of ground water contamination occurred around a lagoon that was in operation for over 8 years in Myatt very fine sandy loam with a clay subsoil, and a lagoon that was in operation 1 mo. prior to this investigation in Dragston fine sandy loam with a sandy clay loam subsoil. Ground water contamination in excess of recommended drinking water standards for Cl and NO_3-N occurred around the third lagoon. This lagoon was in operation for >8 years in a disturbed area consisting of predominantly sandy surface and subsurface soil. Ground water contamination in the embankment area of this lagoon was attributed to seepage and beyond the embankment area to ground water contamination from lagoon overflow.

Copeland, C. & Zinn, J. (1998) Animal waste management and the environment: background for current issues. CRS Report for Congress. Retrieved from http://www.cnie.org/nle/crsreports/Agriculture/ag-48.cfm plus http://www.cnie.org/nle/crsreports/Agriculture/ag-48c.cfm

Abstract: *Waste from animal agriculture is an increasingly prominent environmental quality issue. This background report describes the livestock production industry' today along with public health and environmental concerns related to the industry. It summarizes policies and programs of the Department of Agriculture and the Environmental Protection Agency and recent Clinton Administration initiatives; state laws and programs concerning animal waste management; and dialogues on problems and solutions initiated by some segments of this industry. The report reviews congressional responses to the issues (including two bills 5. 1323 and H.R. 3232) and outlines policy questions likely to shape congressional action. It will be updated if there is major congressional action.*

Culley, J.L.B., & Phillips, P.A. (1982) Sealing of soils by liquid cattle manure. Canadian Agricultural Engineering. 24: 87 -89. Retrieved from http://www.csbe-scgab.ca/docs/journal/24/24_2_87_ocr.pdf

Abstract: *Earthen manure storages are an inexpensive method of storing liquid livestock wastes in the St. Lawrence Lowlands where climatic conditions require that livestock farmers have sufficient capacity to store in excess of 6 mo. of manure production. Percolation tests using liquid dairy manure were performed on soil cores from the parent materials of Kars sand, Grenville loam and Rideau clay to compare their effectiveness as liner material. Hydraulic conductivities of all soil cores decreased to about 0.003 m/day within 5-10 days. The rates of sealing of these soils increased with bulk density; the rate of sealing of the sand was greater than that of the clay or loam. Nitrate plus nitrite N contents of the leachate were generally less than 1 mg/L. Ammonium contents in the leachate from the sand cores were highly variable and averaged about 31 mg/L while those from the clay and loam cores were more consistent and had a mean concentration of about 3 mg/L. The results of this laboratory study suggest that the texture of the soil material selected for the liner itself may have little impact on the extent of groundwater contamination beneath earthen pit storages under saturated conditions.*

DeSutter, T.M., Pierzynski, G.M. & Hamm, J.M. (2005) Movement of lagoon-liquor constituents below four animal-waste lagoons. Journal of Environmental Quality. 34: 1234-1242. doi:10.2134/jeq2004. Retrieved from https://www.soils.org/publications/jeq/abstracts/14/4/JEQ0140040539?access=0&view=pdf

Abstract: *A laboratory study was conducted to determine the degree and rate of sealing of the soil surface where liquid beef (*Bos taurus*) manure with solids content of 50 g* kg^{-1} *was infiltrated into cores of a sandy loam, a loam, and a clay soil under hydraulic heads of 1 and 5 m. A second experiment explored the mechanism of sealing. The infiltration rate was expressed in the logarithmic form of the Kostiakov equation: log* q = A + b *log* t *where* q = *infiltration rate (m* s^{-1}*) and* t = *time (s). In this relation* A *represents the log of the initial infiltration rate (at 1.0 s) and* b *is the rate of change in rate with time on a logarithmic scale. The infiltration rate decreased rapidly with time and reached a value of* 10^{-8} *m* s^{-1} *or less within 30 d on all soils at 1-m hydraulic head. This rate is considered to indicate an essentially impermeable system. At a 5-m head the infiltration rate reached* 10^{-8} *m* s^{-1} *within 10 d on the clay soil but required periods > 30 d on the other two soils. A physical blocking of pores was the major mechanism of sealing. The rate of reduction of infiltration into the loam soil was similar for sterilized manure indicating that in this study biological activity was not a factor. Infiltration of a salt solution having similar cationic constituents as the manure remained constant over time indicating that dispersion of soil particles was not a factor.*

Domansky, J. (2012) Infiltration and water quality impacts associated with wastewater ponds. Texas Digital Library. Retrieved from http://repositories.tdl.org/tdl-ir/handle/2346/9813

Abstract: *The Texas High Plains area during the past 25 years has developed a large cattle feedlot industry that is believed to be a polluter of the surface water and groundwater supplies. It is believed that a natural liner can be formed when manure is placed on top of soil in an agricultural wastewater lagoon. The research contained in this project focused primarily on the infiltration characteristics beneath an integrated facultative pond (IFP) constructed near New Deal, TX. Samplers were placed transversing the cross section of the IFP and the water permeating the soil was monitored for a period from July 27, 1997 to May 30, 1999 and the permeability of the pond was determined. Results show that the pond attained permeability less than the Texas Natural Resources Conservation Commission (TNRCC) regulations of 1 .0 x 10" cm /sec. Additional analysis was conducted to determine what the packed manure layer thickness was at the bottom of the pit. This packed manure layer ranged in thickness from 5 cm to 10 cm in most cases. Additionally, the water that infiltrated into the underlying groundwater supply was monitored for wastewater constituents. This monitoring showed that nitrate nitrogen levels were within the limits established by the National Primary Drinking Water Standards (NPDWS).*

Erickson, D. (1992) Summary of Dairy Lagoon Groundwater Assessments. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e26.pdf

Environmental Investigations Program of Ecology is monitoring four dairy lagoons in Washington State to determine if lagoon leakage affects ground water quality. Two of the lagoons are in Whatcom County near Lynden, one is in Yakima County near Sunnyside, and one is in Lewis County near Chehalis.

Monitoring wells were installed at each lagoon and sampled for a number of parameters (chloride, total dissolved solids, total organic carbon, chemical oxygen demand, total phosphorous, ammonia as N, nitrate + nitrite as N, and total and fecal coliform bacteria).

Table 1 summarizes lagoon construction, ground water conditions, and findings from the first year of monitoring. To date overall conclusions of the study are as follows:

1. Leakage from three of the four lagoons studied has affected groundwater quality to varying degrees. The two lagoons in Whatcom County shoed elevated concentrations for most parameters due to leakage. The lagoon in Yakima County showed elevated concentrations for chloride but long-term effects were probably not observed in the first year of monitoring. The lagoon in Lewis County has not affected ground water quality.

2. Long-term monitoring (2 to 5 years) is needed to understand ground water quality variations near lagoons because of seasonal variability of shallow ground water in agricultural areas.

3. Chloride appears to be a good indicator of leakage from lagoons to ground water.

Erickson, D. (1992) Groundwater Quality Assessment Hornby Lagoon Sunnyside Washington. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e23.pdf

Abstract: The Department of Ecology's Environmental Investigations and Laboratory Services Program (EILS) monitored ground water quality for one year at a new two-stage dairy lagoon (two settling ponds and a main lagoon) in Yakima County. This study was conducted at the request of the Water Quality Program as part of a larger effort to define the impact of dairy lagoons on ground water quality at several locations in Washington State. The results of these studies will be used to augment existing dairy waste management programs.

Monitoring wells were installed and sampled quarterly beginning about three months after initial place of liquid manure. Analytes included chloride, total dissolved solids, total organic carbon, chemical oxygen demand, total phosphate-P, ammonia-N, and nitrate + nitrite – N. The estimated ambient ground water flow velocity ranged from 0.0009 to 0.08 feet per day (0.3 to 29 feet/year) with a geometric mean of about 0.005 feet per day (1.8 feet/year). Chloride concentrations in all wells downgradient of the main lagoon increased after the second and third quarters of monitoring (between four and ten months after the main lagoon received waste water) probably due to leakage from the lagoon. At the onset of monitoring, one well downgradient of the settling ponds showed elevated concentrations of most parameters relative to the upgradient well. Two potential sources for the elevated concentrations are the settling ponds and an old lagoon that was replaced by the new lagoons. The closest water-supply well (located about 200 feet downgradient of the main lagoon) was unaffected during the course of the study. Based on the estimated ground water velocities, the long-term effects of lagoon leakage on ground water quality were probably not observed in the first year of sampling. For this reason, additional monitoring is recommended to determine if concentrations for other parameters increase downgradient of the main lagoon and to determine if chloride concentrations decrease. This

continued monitoring would require authorization by the Water Quality Program based on alignment with their priorities.

Erickson, D. (1992) Groundwater Quality Assessment – Sheridan Dairy Lagoon, Adna, Washington. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e24.pdf

Abstract: Environmental Investigations Program of Ecology monitored ground water quality for one year at a seven-year-old dairy lagoon in Lewis County. Water Quality Program requested this study as part of a larger effort to define the impact of dairy lagoons on ground water quality at four locations in Washington State. The results of these studies will be used to augment existing dairy waste management programs.

Monitoring wells were installed and subsequently sampled quarterly. Analytes included chloride, total dissolved solids, total organic carbon, chemical oxygen demand, total phosphorous, ammonia-N, nitrate + nitrite-N, and total and fecal coliform bacteria. The target aquifer consisted of a thin, confined or semi-confined gravel layer at a depth of about 30 feet, Silt and clay deposits overlie the gravel layer and act to separate the lagoon from the aquifer. The lagoon does not appear to have affected ground water quality to date. Although nitrate + nitrite – N concentrations were elevated relative to upgradient conditions in two downgradient wells none of the other parameters tested, particularly chloride, were elevated.

Erickson, D. (1992) Groundwater Quality Assessment – Whatcom County Dairy Lagoon #2, Lynden, WA. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/92e25.pdf

Abstract: The Environmental Investigations and Laboratory Services Program (EILS) of Ecology monitored ground water quality for one year at a 12-year-old dairy lagoon in Whatcom County. This study was conducted at the request of the Water Quality Program as part of a larger effort to define the impact of dairy lagoons on ground water quality at several locations in Washington State. The results of these studies will be used to augment existing dairy waste management programs.

Monitoring wells were installed, and subsequently sampled quarterly. Analytes included chloride, total dissolved solids, total organic carbon, chemical oxygen demand, total phosphorous, ammonia-N, nitrite + nitrate- N, and total and fecal coliform bacteria. In downgradient wells, concentrations of total dissolved solids, chemical oxygen demand, total organic carbon, ammonia-N, total phosphorous, and chloride consistently exceeded upgradient concentrations, probably due to leakage from the lagoon. Also total and fecal coliform bacteria concentrations in downgradient wells exceeded upgradient conditions intermittently. One downgradient monitoring well showed anomalously high concentrations for one sampling event, probably due to localized leakage from the lagoon. The ground water flow conditions near the lagoon were characterized, and the mean ground water flow velocity was estimated to be about one foot per day. Additional monitoring wells were recommended downgradient of the lagoon to evaluate the fate of contaminants and the distance affected.

Erickson, D. (1992) Edaleen Dairy Lagoon Groundwater Quality Assessment. Washington State Department of Ecology. Retrieved from https://fortress.wa.gov/ecy/publications/publications/91e11.pdf

Abstract: Ground water monitoring was conducted at a new dairy lagoon in Whatcom County for one year. Monitoring wells were installed and sampled prior to placement of liquid manure, and monthly thereafter; the lagoon was sampled quarterly. Samples were tested for chloride, total dissolved solids, total organic carbon, chemical oxygen demand, total phosphate-P, ammonia-N, nitrite + nitrate-N, and total and fecal coliform bacteria. Ground water downgradient of the lagoon showed elevated concentrations for all parameters. With the exception of ammonia-N, concentrations increased to maximal levels and subsequently began to decrease. At the end of the first year of monitoring, concentrations in downgradient wells were still elevated relative to concentrations prior to lagoon use. These observations are consistent with a pulse contaminant source followed by leakage at a lower rate. Ground water velocity estimates at the site ranged from 0.8 to 2.1 feet per day based on chloride travel times. Additional monitoring is recommended to determine if downgradient concentrations decrease to pre-lagoon-use levels and to assure that there are no significant adverse effects on downgradient water-supply wells.

Esser, B. K., Beller, H.R., Carle, S.F., Hudson, G.B., Kane, S.R., Leif, R.N., LeTain, T.E., McNab, W.N. & Moran, J.E. (2009) California GAMA Program: Impact of Dairy Operations on Groundwater Quality. California State water Resources Control Board. Retrieved from http://www.waterboards.ca.gov/gama/docs/ucrl_tr_223509_gamawwfinal_report.pdf

Executive Summary: *A critical component of the California State Water Board's Groundwater Ambient Monitoring and Assessment (GAMA) Program is to assess the major threats to groundwater resources that supply drinking water to Californians (BELITZ et al., 2003). Nitrate is the most pervasive and intractable contaminant in California groundwater and is a focus of special studies under the GAMA program.*

This report assesses the impact of Central Valley dairy operations on underlying groundwater quality and on groundwater processes using new tools developed during the course of the study. During the investigation, samples were collected and analyzed from a total of five dairies in the San Joaquin-Tulare Basins of California: three in Kings County, one in Stanislaus County, and one in Merced County (Figure 1). The study investigated water samples from production wells, monitor wells, and manure lagoons..

The three primary findings of this research are that dairy operations do impact underlying groundwater quality in California's San Joaquin Valley, which dairy operations also appear to drive denitrification of dairy-derived nitrate in these groundwaters, and that new methods are available for characterization of nitrate source, transport and fate in the saturated zone underlying dairy operations.

This study demonstrated groundwater quality impact at three sites using a multi-disciplinary approach, and developed a new tool for source attribution in dairy groundwater. Negative groundwater quality impacts from dairy-derived nitrate were demonstrated using groundwater chemistry, nitrate isotopic composition, groundwater age, and transport modeling. A significant advance in characterization of groundwaters for nitrate source determination was the use of groundwater dissolved gas content to distinguish dairy wastewater irrigation from dairy wastewater lagoon seepage, both of which contributed to dairy groundwater contamination.

The demonstration of saturated-zone denitrification in dairy groundwaters is important in assessing the net impact of dairy operations on groundwater quality. The extent of denitrification can be characterized by measuring "excess" nitrogen and nitrate isotopic composition while the location of denitrification can be determined using a bioassay for denitrifying bacteria that developed in this research. In both northern and southern San Joaquin Valley sites, saturated zone denitrification occurs and mitigates the impact of nitrogen loading on groundwater quality.

Other new methods developed during the course of this study include the field determination of denitrification in groundwater (allowing siting of monitor wells and mapping of denitrifying zones) and characterization of aquifer heterogeneity using direct-push drilling and geostatistics (allowing development of more accurate groundwater transport models). Application of these new methods in conjunction with traditional hydrogeologic and agronomic methods will allow a more complete and accurate understanding of the source, transport and fate of dairy-derived nitrogen in the subsurface.

.

García, A. R., Maisonnave, R. Massobrio, M.J., & Fabrizio de Lorio, A. R. (2011) Field-Scale Evaluation of Water Fluxes and Manure Solution Leaching in Feedlot Pen Soils. Journal of Environmental Quality. 41: 1591–1599 doi:10.2134/jeq2011.0320. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/41/5/1591

Abstract: *Accumulation of beef cattle manure on feedlot pen surfaces generates large amounts of dissolved solutes that can be mobilized by water fluxes, affecting surface and groundwater quality. Our objective was to examine the long-term impacts of a beef cattle feeding operation on water fluxes and manure leaching in feedlot pens located on sandy loam soils of the subhumid Sandy Pampa region in Argentina. Bulk density, gravimetric moisture content, and chloride concentration were quantified. Rain simulation trials were performed to estimate infiltration and runoff rates. Using chloride ion as a tracer, profile analysis techniques were applied to estimate the soil moisture flux and manure conservative chemical components leaching rates. An organic stratum was found over the surface of the pen soil, separated from the underlying soil by a highly compacted thin layer (the manure–soil interface). The soil beneath the organic layer showed greater bulk density in the A horizon than in the control soil and had greater moisture content. Greater concentrations of chloride were found as a consequence of the partial sealing of the manure–soil interface. Surface runoff was the dominant process in the feedlot pen soil, whereas infiltration was the main process in control soil. Soil moisture flux beneath pens decreased substantially after 15 yr. of activity. The estimated minimum leaching rate of chloride was 13 times faster than the estimated soil moisture flux. This difference suggests that chloride ions are not exclusively transported by advective flow under our conditions but also by solute diffusion and preferential flow.*

Glanville, T.D., Baker J.L., Melvin, S.W., & Agua, M.M. (2001) Measurement of leakage from earthen manure structures in Iowa. Transactions of the ASAE 44(6): 1609-1666. Retrieved from http://www.prairieswine.com/pdf/3024.pdf

Abstract: *Leakage from a representative sample of 28 earthen manure storage structures and lagoons (selected from 459 built in Iowa between 1 January 1987 and 31 December 1994) was determined using*

a water–balance approach. Forty–three percent (43%) of tested structures had leakage rates significantly ($p < 0.05$) lower than the regulatory limit of 1.6 mm/d (1/16 in/d) specified by the State of Iowa at the time the basins were constructed. Leakage from 53% of the structures was too close to the regulatory limit to be categorized as being significantly above or below it. One structure (4%) exhibited leakage significantly greater than the regulatory limit. Regression analysis indicates a slight, but statistically significant, decline in leakage rate with increasing structure age. Structures constructed in glacial till showed significantly lower leakage rates than those constructed in sand and gravel, colluvium, or loess. Comparison of slurry pits and lagoons showed no significant difference in leakage rate.

Gooddy, D.C., Clay, J.W., & Bottrell, S.H. (2002) Redox-driven changes in pore water chemistry in the unsaturated zone of the chalk aquifer beneath unlined cattle slurry lagoons. Applied Geochemistry. 17: 903 – 921. doi: 10.1016/S0883-2927(2)00055-0. Retrieved from http://www.sciencedirect.com/science/article/pii/S0883292702000550

Abstract: *Farm waste stores such as cattle slurry lagoons are widespread in the UK and many overly important aquifers. Stores can be serious risks to water quality because they are important sources of N species, organic C and pathogenic microbes. At two sites on the Chalk aquifer of southern England, inclined boreholes were drilled and cored to obtain aquifer material from directly beneath unlined slurry stores. Vertical boreholes were also drilled adjacent to the slurry stores to determine any lateral movement of contaminants. Interstitial porewaters were analyzed for major and minor ions and S isotopes. At the second site, unsaturated zone gases were sampled from the inclined hole. Infiltration of slurry into the unsaturated zone caused significantly elevated concentrations of metals such as Cu and Ni at both sites. Sulphate reduction was occurring at Site 1, as evidenced by SO_4 concentrations decreasing from 150 to 50 mg/l and enhanced ratios of $\delta^{34}S–SO_4$ and $\delta^{18}O–SO_4$. Ammonium-N also leaches along with dissolved organic C which were found 17 m below ground surface at concentrations up to 400 and 260 mg/l, respectively. Contaminant concentrations were similar in the porewaters from both the inclined and vertical boreholes. At Site 2, higher contaminant concentrations were found in the inclined borehole compared with the vertical borehole. Organic C concentrations were considerably lower than at Site 1, ranging from 10 to 70 mg/l. Ammonium–N concentrations reached a maximum concentration of 25 mg/l; however NO_3-N concentrations were up to 500 mg/l and SO_4 concentrations were generally higher than Site 1. Data for N_2/Ar and $\delta^{15}N–N_2$ from the gas samplers show a peak of 102 and 2.2‰, respectively, at 14 m below ground level indicating denitrification was taking place. Evidence from $\delta^{34}S–SO_4$ and $\delta^{18}O–SO_4$ suggest that some SO_4 reduction was taking place simultaneously. From CH_4 and NH_3 detected at depth it is suggested that slurry contamination, emanating from early use of the store, has passed through the top 18 m of the unsaturated zone at Site 2. The presence of high concentrations of NO_3 and lower concentrations of organic C suggests that this lagoon has formed a relatively impermeable seal at its base within the first few years of its lifetime. The anoxic conditions at both sites may have mobilised U from N–P–K fertilisers. Both sites are continuing to impact on the porewater chemistry and pose a risk of groundwater contamination.*

Gooddy, D.C., Hughes, A.G., Williams, A.T., Armstrong, A.C., Nicholson, R.J. & Williams, J.R. (2001) Field and modeling studies to assess the risk to UK groundwater from earth-based stores for livestock manure. Soil Use Management. 17: 128 – 137. doi: 10.1111/j.1475 – 2743.2001.tb00018x. Retrieved from Retrieved from http://nora.nerc.ac.uk/7770/2/Manuscript_F%26M_Studies.pdf

Abstract: *Boreholes have been constructed at eight sites on the Permo-Triassic Sandstone and Chalk aquifers to assess the extent of chemical and microbiological contamination emanating from unlined farm manure stores. Slurry along fracture faces in the Chalk was found on cores taken from beneath two stores. Porewaters from the Chalk sites and one of the Sandstone sites were discoloured and showed high concentrations of nitrate, ammonium and organic carbon to depths in excess of 10 m. Although Cryptosporidia and E.coli O157 were found in many of the cattle slurry lagoons, neither were found in the aquifer material beneath. The self-sealing of unlined slurry stores is seen as a crucial step in minimizing leakage. A simple mass balance shows farm boreholes near to contaminant sources are at greater risk than public supply wells. Contaminant modeling shows discontinuing use of an unlined farm manure store will lead to little difference in solute concentrations over the short to medium term. Groundwater is most at risk where the water table is shallow since direct hydraulic connection between the lagoon base and the water table considerably increases the rate of vertical migration. This is of greatest significance for pathogens that are thought to be relatively short lived in the subsurface. Under the majority of situations minimal threat is posed to potable groundwater drinking supplies.*

Gooddy, D.C., Withers, P.J.A., McDonald, H.G. & Chilton, P.J. (1998) Behavior and impact of cow slurry beneath a storage lagoon: II. Chemical composition of chalk porewater after 18 years. Water Air Soil Pollution. 107: 51 – 72. doi: 10.1023/A:1004975615804. Retrieved from http://link.springer.com/article/10.1023%2FA%3A1004975615804?LI=true#page-1 and http://nora.nerc.ac.uk/7768/

Abstract: *To determine the pollution hazard associated with the long-term storage of cow slurry, two boreholes were drilled to a depth of nearly 35 m in the unsaturated zone of the Upper Chalk beneath an unlined, earth-banked lagoon. Chalk porewater was extracted by centrifugation from successive 0.45 m length core sections and their chemical and biological composition determined. Porewaters from the first borehole, which was cited in the deepest part of the lagoon, were discoloured and showed the highest concentrations of bicarbonate (HCO3), dissolved organic carbon (TOC), ammonium-nitrogen (NH4-N) and organic phosphorus (P-o) in the first 6 m directly beneath the base of the lagoon. Below this depth, element concentrations decreased more sharply and amounts of nitrate-nitrogen (NO3-N) increased. Porewaters from the second borehole, which was sited at the edge of the lagoon, were almost colourless and showed less elevated concentrations of determinants compared to the first borehole with the exception of NO3-N. However, large increases in TOC, NH4-N and P-o were observed at 29 m in the second borehole indicating that the borehole had intercepted slurry which had migrated rapidly through the chalk profile by preferential how along fissures in the Chalk. There was visible evidence of slurry contamination on fissure faces of chalk teres extracted from both boreholes. Microbial activity was detected only on fissure faces and not in the porewaters of either borehole. However microbially mediated reactions were important in terms of the chemical transformations (organic carbon oxidation, nitrification, nitrate reduction) taking place beneath the lagoon.*

Ham, J.M. & DeSutter, T.M. (1999a) Seepage Losses and Nitrogen Export from Swine-Waste Lagoons: A Water Balance Study. Journal of Environmental Quality 28(4): 1090 – 1099. Abstract retrieved from https://www.soils.org/publications/jeq/abstracts/28/4/JEQ0280041090?access=0&view=pdf

Abstract: *Seepage losses from animal-waste lagoons could affect ground water quality. Water balance methods were used to study seepage and N export from three swine-waste lagoons in southwestern Kansas. Lagoons ranged in size from 0.8 to 2.2 ha and had an average waste depth of 5.6 m. Compacted soil liners were 0.30 to 0.46 m thick and built with native soil or, in one case, a soil-bentonite mixture. Seepage was calculated from measurements of evaporation and changes in depth when the addition or removal of waste was precluded or quantified. Seepage rates were 1.1, 1.1, and 0.8 mm d^{-1} from the three lagoons, with the lowest rate occurring at the site with a 0.46-m liner augmented with bentonite. The in situ coefficient of permeability of the soil liners ranged from 7.8×10^{-8} and 1.5×10^{-7} cm s^{-1}. In two lagoons built with silt loam liners (no bentonite), permeabilities on a whole-lagoon basis were about five times less than those measured from soil cores collected before the addition of waste. Results imply that permeability was reduced by organic sludge on the bottom of the lagoons. The average ammonium-N concentration in the lagoons was 665 mg L^{-1}, accounting for almost all of the soluble N. Calculations indicate that the ammonium-N export rates were between 2187 and 2726 kg ha^{-1} yr^{-1}, but more information is needed regarding the fate of N deposited in the soil beneath lagoons.*

Ham, J.M. (1999b) Measuring evaporation rates and seepage losses from lagoons used to contain animal waste. Transactions of the ASAE 42(5): 1303 – 1312. Retrieved from http://www.soilcrop.colostate.edu/ham/pdf_files/ham1999.pdf

ABSTRACT. *Seepage (S) from animal-waste lagoons was estimated using a water balance approach by measuring changes in waste level (i.e., depth) (ΔD) and evaporation (E) over brief periods (e.g., 6 days) when all other inflow and outflow were precluded. Data were collected at commercial swine and cattle feedlots in southwestern Kansas. Precision waste level recorders, floating evaporation pans, and meteorological models were used to measure each lagoon's water balance. Different strategies for calculating evaporation and seepage were compared. Initial work at a 2.5-ha plastic-lined lagoon (S = 0, E ≈ 5.1 mm d–1) showed that evaporation over 6- to 11-day periods could be measured to within ±0.5 mm d–1 with floating evaporation pans using a pan coefficient of 0.81. A bulk-transfer evaporation model, which incorporated realtime measurements of lagoon surface temperature, predicted evaporation to within 6% when using a transfer coefficient of 2.8 × 10–3. Evaporation models that did not include surface temperature resulted in significant errors (e.g., > 50%) under certain environmental conditions. The water balance of a soil-lined, cattle-feedlot lagoon over an 11-day period was: ΔD = 2.1; E = 1.9, and S = 0.2, all in mm d–1. Additional work over a 6-day period at a soil-lined, swine-waste lagoon resulted in a water balance of: ΔD = 5.4; E = 4.5, and S = 0.9, all in mm d–1. Data suggest that seepage from lagoons can be determined to within ±0.5 mm d–1 by making precision water balance measurements over short periods (5 to 10 days), if evaporation is less than 6 mm d–1.*

Ham, J.M. (2002) Seepage losses from animal waste lagoons: A summary of a four year investigation in Kansas. Trans. ASAE 45: 983 – 992. Retrieved from http://www.prairieswine.com/pdf/3034.pdf

ABSTRACT. *Seepage losses from animal waste lagoons can affect groundwater quality if liquid effluent is not properly contained within the basin. Seepage rates from 20 anaerobic lagoons were measured using water balance methods. Study locations included 14 swine sites, 5 cattle feedlots, and a single dairy. Seepage results and basin geometry were used to estimate the hydraulic conductivity (Ks) of the compacted soil liner at each site. Seepage data and waste chemistry were used to calculate rates of chemical export into the vadose zone. Profiles of ammonium–nitrogen (N) and other chemicals were determined by sampling soils beneath old lagoons. Seepage rates from 20 lagoons averaged 1.1 mm/d and ranged from 0.2 to 2.4 mm/d. Fifteen of the 20 lagoons had seepage rates between 0.5 and 1.5 mm/d. The variation among locations was small despite large differences in soil types and depths to groundwater. On average, the Ks of lagoon liners was 1.8 Ü 10–7 cm/s. Variation in seepage rates and Ks among sites was log normally distributed. There was evidence that seepage was moderated by the organic sludge that blankets the bottom of lagoons. Concentrations of nitrogen, phosphorus, and other waste constituents were, on average, 3 to 5 times higher in swine waste lagoons compared to cattle feedlot lagoons. Ammonium–N seepage into the subsoil ranged from 2000 to 5000 kg ha–1 yr.–1 at the larger swine sites but averaged 385 kg ha–1 yr.–1 at cattle feedlots. Soil cores showed that concentrations of ammonium–N, organic–N, phosphorus, and other cations were highest near the original floor of the lagoon but decreased markedly with depth. In most cases, concentrations of nutrients in the soil returned to background levels about 3 m under the lagoons. Additional research is needed on fate and transport of contaminants that accumulate beneath lagoons and best management practices for lagoon closure.*

Ham, J. M., & Baum, K.A. (2009) Measuring seepage from waste lagoons and earthen basins with an overnight water balance test. Trans ASAE 53: 835 – 844. Trans. ASAE 52: 835 – 844. Retrieved from Retrieved from http://soilcrop.colostate.edu/ham/pdf_files/Ham_Baum_2009.pdf

ABSTRACT*: Previous work demonstrated that whole-lagoon seepage rates could be determined by measuring the difference between the change in depth and cumulative evaporation over a 5-day period when waste inputs are withheld. However, faster techniques are needed to make the approach more cost effective and more logistically feasible at sites that can halt waste inputs for only 1 to 2 days. Research was conducted to develop a simplified overnight water balance test. Data were collected at several earthen-lined waste storages in Kansas. Evaporation was measured by eddy covariance and compared with that estimated by the bulk transfer equation; infrared measurements of waste surface temperature and weather data collected on the lagoon berm were used as inputs. Pressure probes and a float recorder were installed near the shoreline to measure depth changes. Data from berm-deployed weather stations were adequate for predicting evaporation with the bulk transfer equation, provided wind speed was downscaled by 27% to represent conditions near the waste surface. Depth sensors positioned on the upwind and downwind sides of the basin agreed when winds speeds were less than about 3 m s-1. Nighttime (2130 to 0630 h) evaporation ranged from 0.2 to 2.2 mm in May and June. Good agreement in the seepage estimates was found among tests conducted on consecutive nights at the same lagoon. Confidence in the seepage estimate was increased by repeating the overnight test for two consecutive or near-consecutive nights.*

Ham, J.M., & DeSutter, T.M. (2000) Toward site-specific design standards for animal-waster lagoons: Protecting ground water quality. Journal of Environmental Quality. 29: 1721 – 1732. doi: 10.2134/jeq2000.00472425002900060001x. Retrieved from

https://www.agronomy.org/publications/jeq/abstracts/29/6/JEQ0290061721?access=0&view=pdf and http://state-cafos.org/docs/HamDeSutter2000.pdf

Abstract: *Seepage losses from animal-waste lagoons can affect ground water quality, if facilities are not properly sited, designed, and constructed. Most states in the Great Plains stipulate that earthen lagoons cannot seep more than some specified rate (mm d^{-1}). These criteria often apply to the entire state and all livestock species, although ground water vulnerability and waste characteristics are highly variable from site to site. Because of this variability, statewide "blanket" regulations may overregulate some producers and under regulate others. Furthermore, wide disparity exists in seepage allowances among neighboring states, and regulations often are influenced by public opinion rather than scientific findings. This paper argues that lagoon design should be site specific and presents a logical framework to determine the maximum allowable seepage rate for a given location and type of operation (e.g., dairy, swine, cattle feedlot). Site-specific factors, such as soil properties, depth to water table, and chemistry of the waste, are used to arrive at lagoon performance standards that minimize long-term risk. The decision process within the framework is presented as a conceptual model for lagoon permitting and may need to be customized to meet the requirements of each state. Nevertheless, use of site-specific design criteria will ensure that manure storages are adequate (e.g., plastic-lined lagoons) in regions with vulnerable ground water, while providing reduced lagoon construction costs (lower cost of soil-lined lagoons) for producers who site their operations in areas of low risk. To complement the site-specific approach, the whole-lagoon seepage rate should be measured after construction to verify that the prescribed performance criteria have been met.*

Ham, J.M., Reddi, L.M. & Rice, C.W. (1999) Animal waste water quality study. Kansas State University and the Kansas Water Office. Retrieved from http://www.ksre.ksu.edu/bookstore/pubs/LAGOON.pdf

ABSTRACT. *Seepage (S) from animal-waste lagoons was estimated using a water balance approach by measuring changes in waste level (i.e., depth) (ΔD) and evaporation (E) over brief periods (e.g., 6 days) when all other inflow and outflow were precluded. Data were collected at commercial swine and cattle feedlots in southwestern Kansas. Precision waste level recorders, floating evaporation pans, and meteorological models were used to measure each lagoon's water balance. Different strategies for calculating E and S were compared. Initial work at a 2.5-ha plastic-lined lagoon (S = 0, E ≈5.1 mm d-1) showed that E over 6- to 11-day periods could be measured to within ±0.5 mm d-1with floating evaporation pans using a pan coefficient of 0.81.*
A bulk-transfer evaporation model, which incorporated real-time measurements of lagoon surface temperature, predicted E to within 6 % when using a transfer coefficient of 2.8x10-3. Evaporation models that did not include surface temperature resulted in significant errors (e.g., >50 %) under certain environmental conditions. The water balance of a soil-lined, cattle-feedlot lagoon over an 11-day period was: ΔD=2.1; E=1.9, and S= 0.2, all in mm d-1. Additional work over a 6-day period at a soil-lined, swine-waste lagoon resulted in a water balance of: ΔD = 5.4; E=4.5, and S = 0.9, all in mm d-1.Data suggest that S from lagoons can be determined to within±0.5 mm d-1by making precision water balance measurements over short periods (5 to 10 days),if E is less than 6 mm d-1.

Harter, T., Davis, H., Mathews, M.C. & Meyer, R.D. (2002) Shallow groundwater quality on dairy farms with irrigated forage crops. Journal of Contamination Hydrology. 55: 287 – 315. doi: 10.1016/S0169-7722(01)00189-9. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11999633

Abstract: *California's dairies are the largest confined animal industry in the state. A major portion of these dairies, which have an average herd size of nearly 1000 animal units, are located in low-relief valleys and basins. Large amounts of liquid manure are generated and stored in these dairies. In the semi-arid climate, liquid manure is frequently applied via flood or furrow irrigation to forage crops that are grown almost year-round. Little is known about the impact of manure management practices on water quality of the extensive alluvial aquifers underlying these basins. The objective of this work is to assess nitrate and salt leaching to shallow groundwater in a relatively vulnerable hydrogeologic region and to quantify the impact from individual sources on dairies. The complex array of potential point and nonpoint sources was divided into three major source areas representing farm management units: (1) manure water lagoons (ponds); (2) feedlot or exercise yard, dry manure, and feed storage areas (corrals); and (3) manure irrigated forage fields (fields). An extensive shallow groundwater-monitoring network (44 wells) was installed in five representative dairy operations in the northeastern San Joaquin Valley, CA. Water quality (electrical conductivity, nitrate-nitrogen, total Kjehldahl nitrogen) was observed over a 4-year period. Nitrate-N, reduced nitrogen and electrical conductivity (EC, salinity) were subject to large spatial and temporal variability. The range of observed nitrate-N and salinity levels was similar on all five dairies. Average shallow groundwater nitrate-N concentrations within the dairies were 64 mg/l compared to 24 mg/l in shallow wells immediately upgradient of these dairies. Average EC levels were 1.9 mS/cm within the dairies and 0.8 mS/cm immediately upgradient. Within the dairies, nitrate-N levels did not significantly vary across dairy management units. However, EC levels were significantly higher in corral and pond areas (2.3 mS/cm) than in field areas (1.6 mS/cm) indicating leaching from those management units. Pond leaching was further inferred from the presence of reduced nitrogen in three of four wells located immediately downgradient of pond berms. The estimated minimum average annual groundwater nitrate-N and salt loading from manure-treated forage fields were 280 and 4300 kg/ha, respectively. Leaching rates for ponds are estimated to be on the order of 0.8 m/year, at least locally. Since manure-treated fields represent by far the largest land area of the dairy, proper nutrient management will be a key to protecting groundwater quality in dairy regions overlying alluvial aquifers.*

Huffman, R.L. (2004) Seepage evaluation of older swine lagoons in North Carolina. Transactions of the ASAE. 47(5): 1507−1512. Retrieved from http://www.prairieswine.com/pdf/3112.pdf

Abstract: *Thirty−four swine waste lagoon systems in North Carolina were examined for evidence of seepage losses to the shallow groundwater. All were constructed prior to the state's January 1993 adoption of stricter construction standards. Mineral nitrogen concentrations (ammoniacal plus nitrate nitrogen) were used as the primary indicators of seepage impacts. Total mineral concentrations were compared to the U.S. EPA drinking water standard for nitrate−N of 10 mg/L. The shallow ground-water on approximately one−third of the 34 systems met the EPA standard at a distance of 38 m (125 ft) downgradient from the lagoon(s)*

Jones, D.D., Koelsch, R.K., Mukhtar, S., Sheffield, R. & Worley, J.W. (2006) Closure of earthen manure structures (Including basins, holding ponds and lagoons). Conference Presentations and White Papers. Biological Systems Engineering. Retrieved from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1003&context=biosysengpres&sei-redir=1&referer=http%3A%2F%2Fscholar.google.com%2Fscholar%3Fq%3DInfluence%2Bof%2Bseal%2Band%2Bliner%2Bhydraulic%2Bproperties%2Bon%2Bthe%2Bseepage%2Brate%2Bfrom%2Banimal%2Bwaste%2Bholding%2Bponds%2Band%2Blagoons%26btnG%3D%26hl%3Den%26as_sdt%3D0%252C48%26as_vis%3D1#search=%22Influence%20seal%20liner%20hydraulic%20properties%20seepage%20rate%20from%20animal%20waste%20holding%20ponds%20lagoons%22

***Abstract**: This paper is a summary of what is known scientifically about the closure of earthen manure structures without artificial liners, including lagoons, storage basins, and runoff holding ponds, and what needs to be examined further to increase our understanding of the dynamics of closing them in an environmentally safe manner. This information should be useful as a guide for state regulatory agencies considering rules for closure and for academicians and consultants who work with live-stock production facilities.*

Korom, S.F. & Jeppson, R.W. (1994) Nitrate contamination from dairy lagoons constructed in coarse alluvial deposits. Journal of Environmental Quality. 23: 973 – 976. doi: 10.2134/jeq1994.00472425002300050018x. Abstract retrieved from https://www.crops.org/publications/jeq/abstracts/23/5/JEQ0230050973?access=0&view=pdf and https://www.agronomy.org/publications/jeq/abstracts/23/5/JEQ0230050973

***Abstract:** In an effort to reduce surface inflows of nutrients to Deer Creek Reservoir in north central Utah, several dairies in Heber Valley constructed unlined lagoons to store wastes for later application onto fields as fertilizer. Previous research indicated that dairy lagoons sealed with use and were not significant sources of contamination; however, the soils in Heber Valley are coarser than in the literature. Therefore, two of Heber Valley's dairy lagoons were studied as sources of NO^-_3-N to the groundwater system. One lagoon was constructed on Holmes subsoils (loamy-skeletal, mixed, frigid Typin Argixerolls); its seepage rate was estimated at 13 to 91 mm/d, which is as high or higher than any of the rates reported in the literature. The other lagoon was constructed on Deer Creek subsoils (fine, montmorillonitic, frigid Typic Palexerolls). Leachate quality from both lagoons typically exceeded the drinking water standard of 10 mg NO^-_3-N/L and sometimes exceeded 100 mg NO^-_3-N/L. The likely reason for the high NO^-_3-N concentrations was that the coarse soils in Heber Valley sometimes permitted the aerobic conditions necessary for nitrification of immobile NH^+_4 to mobile NO^-_3. We concluded that the unlined dairy lagoons were significant sources of N (as NO^-_3) contamination to the Heber Valley aquifer.*

Libra, R.L., Quade, D.J. & Seigley, L.S. (n.d.) Groundwater monitoring at earthen manure-storage structures in Iowa. Iowa Dept. of Natural Resources. Retrieved from http://www.igsb.uiowa.edu/Mapping/kirkwood/kirkwood.htm

***Abstract:** Groundwater has been monitored monthly since 1993 at three earthen manure storage structures in Iowa. Seepage has been detected in all downgradient wells at the Des Moines Lobe site in north-central Iowa (earthen basin) and at the Iowan Surface site in east-central Iowa (2-cell earthen*

lagoon). Indications of seepage are similar and include: the decline or loss of nitrate-N and sulfate, and an increase in concentrations of chloride and total organic carbon. Chloride concentrations in the berm well at the north-central Iowa site are 40% of those measured in the liquid waste; at the east-central Iowa site, concentrations at the closest well are 80% of those in the waste. Fecal coliform bacteria have been sporadically detected in the closest well at the north-central Iowa site. Concentrations of nutrients, such as ammonia-N, initially did not increase, indicating these species were being retained by cation (positively charged ion) exchange. However, ammonia-N concentrations have recently shown increases, suggesting the exchange capacity is being depleted. Organic-N concentrations have increased, and are typically higher than ammonia-N concentrations. Exchange reactions that limit ammonia-N transport result in a build-up of ammonia-N beneath an earthen manure-storage structure. At the allowable seepage rate of 1/16th inch/day, a basin like the one used at the north-central Iowa site (4,500-head hog finishing operation) would transport 5,300 pounds of ammonia-N to the glacial materials beneath the ½-acre basin annually.

McCurdy, M. & McSweeney, K. (1993) The origin and identification of macropores in an earthen=lined manure storage basin. Journal of Environmental Quality. 22(1): 148 – 154. Abstract retrieved from https://www.soils.org/publications/jeq/abstracts/22/1/JEQ0220010148?access=0&view=pdf

Abstract: *Earthen-lined basins have been used to store dairy manure in Wisconsin since the early 1970s. Monitoring data indicate that many of these basins are leaking, but little effort has been directed toward explaining the mechanisms responsible for leakage. Morphological and micromorphological techniques were used to identify macropores in the sidewall of an earthen-lined manure storage basin. Laboratory and field dye studies provided evidence of contaminant movement via macropores. Results indicate that physicochemical and biological mechanisms were responsible for creating macropores capable of providing pathways for preferential flow. These mechanisms, and the resulting macropores, can significantly affect the long-term viability of earthen-lined manure storage basins.*

McNab, W.W., Singleton, M.J., Moran, J.E. & Esser, B.K. (2006) Assessing the impact of animal waste lagoon seepage on the geochemistry of an underlying shallow aquifer. Environmental Science and Technology. Retrieved from https://e-reports-ext.llnl.gov/pdf/331439.pdf

Abstract: *Dairy facilities and similar confined animal operation settings pose a significant nitrate contamination threat via oxidation of animal wastes and subsequent transport to shallow groundwater. While nitrate contamination resulting from application of animal manure as fertilizer to fields is well recognized, the impact of manure lagoon leakage on groundwater quality is less well characterized. In this study, a dairy facility located in the southern San Joaquin Valley of California has been instrumented with monitoring wells as part of a two-year multidisciplinary study to evaluate nitrate loading and denitrification associated with facility operations. Among multiple types of data collected from the site, groundwater and surface water samples have been analyzed for major cations, anions, pH, oxidation-reduction potential, dissolved organic carbon, and selected dissolved gases (CO2, CH4, N2, Ar, Ne). Modeling of putative geochemical processes occurring within the dairy site manure lagoons shows substantial off-gassing of CO2 and CH4 in response to mineralization of organic matter. The gas*

ebullition appears to strip dissolved gases, including Ar and Ne, from the lagoon water leaving concentrations that are under saturated with respect to the atmosphere. The resulting fractionated dissolved gas signature serves as an effective tracer for the lagoon water in the underlying shallow groundwater and can be used to constrain inverse geochemical models that assess mixing fractions of lagoon water and local groundwater water. Together with ion exchange and mineral equilibria reactions, identification of lagoon seepage helps explain key attributes of the local groundwater chemistry, including input and cycling of nitrogen, across the site.

Meyer, J.L., Olson, E., & Baier, D. (1972) Manure holding ponds found self-sealing. California Agriculture. 26: 14 – 15. Retrieved from http://ucce.ucdavis.edu/files/repositoryfiles/ca2605p14-69365.pdf

Abstract: *Waste ponds can be utilized to economically handle dairy and poultry waste waters. Usually the effluent from the ponds is used later for irrigation. Sometimes the effluent is recycled by reusing it for subsequent flushing. Whatever the mode of operation of the ponds, it is important to know how much, if any, deep percolation occurs; what is the fate of nitrogenous substances; what are the changes in other chemical constituents; and what bacterial processes occur in the ponds. This report outlines some preliminary findings in a study of operation of waste ponds, and delineates subsequent necessary research to evaluate their total impact on the environment. The most significant of these findings was that there was hardly any seepage of water from manure- laden ponds in this study, and that artificial seals were not needed under these soil conditions*

Miller, M.H., Robinson, J.B., & Gillham, R.W. (1985) Self-sealing of earthen liquid manure storage ponds. 1. A case-study. Journal of Environmental Quality. 14: 533 – 538. doi:10.2134/jeq1985.00472425001400040013x. Retrieved from https://www.agronomy.org/publications/jeq/abstracts/14/4/JEQ0140040533 and https://www.crops.org/publications/jeq/abstracts/14/4/JEQ0140040533?access=0&view=pdf

Abstract: *A monitoring system was established on an unlined, earthen storage pond near Kitchener, ON prior to the addition of liquid manure from a 4500-head beef (*Bos taurus*) feeding operation. The bottom of the pond, which had a surface area when full of 2 ha, was a coarse textured sand. This material, with some gravel layers, extended below the water table, which was initially at 13.7 m below the ground surface. A platform, at which soil moisture measurement and groundwater sampling tubes were installed, was constructed within the pond. Additional groundwater sampling tubes were installed at several points surrounding the pond. Moisture content of the soil immediately below the pond reached saturation when liquid manure was first added but began to decrease within 2 weeks and reached a steady state at a water potential of about −0.03 MPa within 90 d. The infiltration rate at this time was estimated to be less than 10^{-8} m s^{-1}, a value considered to indicate that the bottom was effectively sealed. There was a rapid increase in Cl content of the groundwater within 2 weeks of manure addition but the concentration declined to initial values within 12 weeks. There was no evidence of elevated Cl concentrations in groundwater outside the boundaries of the pond. The NO_3-N content of groundwater below the pond decreased to non-detectable values very shortly after addition of manure but returned to background values within 12 weeks except in the upper portions of the groundwater. A similar depression of NO_3-N was observed at one sampling position within a few meters of the pond but not at more distant points. It was concluded that the NO_3-N depression was due primarily to denitrification in*

the groundwater as it passed below the pond. It is concluded that, with some limitations, unlined earthen manure ponds are environmentally acceptable, even in sandy material.

Miller, M. H., J. B. Robinson, and D. W. Gallagher. "Accumulation of nutrients in soil beneath hog manure lagoons." Journal of Environmental Quality 5 (3): 279-82. Abstract Retrieved from http://www.pork.org/ResearchDetail/1073/AccumulationofNutrie.aspx#.UWCUecpXr5Q

Abstract: *The soil beneath four hog manure lagoons was sampled and analyzed for NO3-N, NH4-N and soluble P. Nitrate levels were essentially zero in all samples taken shortly after the lagoons were emptied. Soluble P levels were high immediately below the lagoon but decreased to background levels within 20-30 cm. Ammonium levels were very high immediately below the lagoon. The levels decreased to background levels within 20-30 cm on two lagoons on fine-textured soils that had been in use for two years. In a medium-textured soil and a coarse-textured soil beneath older lagoons, very high levels existed to the maximum depth samples. It is suggested that this accumulation of NH4-N presents a serious hazard should the lagoon be abandoned and the soil become aerobic. Earthen manure lagoons should not be recommended on medium or coarse-textured soils.*

Nolan, B. T., B. C. Ruddy, K. J. Hitt, and D. R. Helsel. 1997. Risk of nitrate in groundwaters of the United States-A national perspective. Environ. Sci. Technol. 31:2229-2236. Retrieved from http://water.usgs.gov/nawqa/nutrients/pubs/est_v31_no8/est_v31_no8.pdf

Abstract: *Nitrate contamination of groundwater occurs in predictable patterns, based on findings of the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) Program. The NAWQA Program was begun in 1991 to describe the quality of the Nation's water resources, using nationally consistent methods. Variables affecting nitrate concentration in groundwater were grouped as "input" factors (population density and the amount of nitrogen contributed by fertilizer, manure, and atmospheric sources) and "aquifer vulnerability" factors (soil drainage characteristic and the ratio of woodland acres to cropland acres in agricultural areas) and compiled in a national map that shows patterns of risk for nitrate contamination of groundwater. Areas with high nitrogen input, well-drained soils, and low woodland to cropland ratio have the highest potential for contamination of shallow groundwater by nitrate. Ground- water nitrate data collected through 1992 from wells less than 100 ft deep generally verified the risk patterns shown on the national map. Median nitrate concentration was 0.2 mg/L in wells representing the low-risk group, and the maximum contaminant level (MCL) was exceeded in 3% of the wells. In contrast, median nitrate concentration was 4.8 mg/L in wells representing the high-risk group, and the MCL was exceeded in 25% of the wells*

North Carolina Division of Water Quality (1998) Impact of Animal Waste Lagoons on Groundwater Quality. Retrieved from http://portal.ncdenr.org/c/document_library/get_file?uuid=51d2c023-99c3-47c9-a8fb-834bfcd14c6f&groupId=38364

Executive Summary: *The objective of the North Carolina Division of Water Quality's study on the "Impact of Animal Waste Lagoons on Ground Water Quality" is to determine whether federal construction standards used by North Carolina regulatory agencies for animal waste management lagoons offer adequate ground water protection. Funded by the Environmental Protection Agency in 1994, the study reviews building requirements that the U.S. Natural Resources and Conservation Service uses for new waste lagoons. The EPA provided $94,500 in funding for the research. DWQ's Groundwater Section evaluated 11 sites during this study, of which nine were hog farms and two were dairy operations. Results from a 12th site were not considered valid because the monitoring wells needed to be located further downstream to better reflect potential effects. Vulnerability criteria were used to assess potential ground water contamination. Five of the farms were considered to be "less vulnerable," four were deemed "moderately vulnerable" and two were viewed as "vulnerable." Of the five less vulnerable sites, none of the downgradient shallow monitoring wells that the Division installed revealed any seepage problems from the lagoons. Wells at three of the four moderately vulnerable farms showed an increasing trend in concentrations of one or more lagoon seepage indicators, such as nitrates and chlorides. Wells at one of the two vulnerable sites revealed lagoon seepage contamination from ammonia, potassium and nitrates. Only limited conclusions can be drawn from this study because a larger sampling group is needed and sufficient time must be allowed for ground water movement beneath lagoons to the monitoring wells. The Groundwater Section has since acquired $50,000 additional funding from EPA to continue monitoring at the 11 sites. Study results are expected in 2001.*

Nunez-Delgado, A., Lopez-Periago, E., Diaz-Fierro-Viquiera, F. (2002) Pollution attenuation by soils receiving cattle slurry after passage of a slurry-like feed solution.: Column experiments. Bioresource Technology 84(3): 229 – 236. Abstract Retrieved from http://www.sciencedirect.com.ezp.waldenulibrary.org/science/article/pii/S0960852402000500

Abstract: *Designing soil filtration systems or vegetated filter strips as a means of attenuating water pollution should take into account soil purging capacity. Here we report data on laboratory column trials used to investigate the capacity of a Hortic Anthrosol to attenuate contamination due to downward leaching from cattle slurry applied at the surface. The columns comprised 900 g of soil to a depth of about 20–25 cm, and had been used previously in an experiment involving passage of at least 5 pore volumes of an ion-containing cattle slurry-like feed solution. For the present experiments, the columns were first washed through with distilled water (simulating resting and rain falling after passage of the feed solution), and then received a single slurry dose equivalent to about 300 m^3 ha^{-1}. The columns were then leached with distilled water, with monitoring of chemical oxygen demand (COD) and ion contents in outflow. The results indicated that the pollution-neutralising capacity of the soil was still high but clearly lower than in the earlier experiments with the feed solution. Furthermore, the time-course of COD showed that organic acids were leached through the column even more rapidly than chloride (often viewed as an inert tracer) enhancing the risk of heavy metals leaching and*

subsequent water pollution. Resting and alternate use of different soil-plant buffer zones would increase the lifespan of purging systems that use soil like the here studied one.

Oliver, J.C. & Meyer, J.L. (1974) Subfloor monitoring of Shady Grove dairy liquid manure holding pond. California Agriculture, 28: 6-7. Retrieved from http://ucce.ucdavis.edu/files/repositoryfiles/ca2804p6-64108.pdf

Abstract: *This report of the subfloor monitoring of the Shady Grove Dairy liquid manure holding pond near Chino offers further proof that such ponds are self-sealing and allow little or no seepage.*

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999a) Modeling seepage from an unlined beef cattle feedlot runoff storage pond. Trans. ASAE 42: 1437 – 1445. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=1353660

Abstract: *A site-specific water balance model was developed to evaluate the effects of sludge accumulation, starting stage, and annual precipitation on seepage from an unlined beef cattle feedlot runoff storage pond. The computer model predicted daily inflows due to precipitation and runoff, and outflows due to evaporation and seepage. The seepage component was estimated using the SWMS—2D finite element saturated/unsaturated flow model, while feedlot runoff was estimated using the Natural Resource Conservation Service runoff method. Evaporation, precipitation, and temperature data from a nearby weather station were used in the model. Based on results of 9,100 annual simulations, the mean seepage volume ranged from 31 900 m^3/y with no sludge accumulation to 19300 m^3/y with 22 years of sludge accumulation (1.5 m of sludge). The mean seepage rate ranged from 1.11 cm/day with no sludge accumulation to 0.50 cm/day with 22 years of sludge accumulation. Sidewall seepage volumes ranged from 49 to 73% of the total pond seepage volume. Increasing the pond stage from 0 to 250 cm at the beginning of the simulations caused a 200% increase in annual seepage volumes, yet only a 20% increase in annual seepage rates. Annual seepage volumes increased as much as 62% when annual precipitation increased from 44 to 96 cm/y. Average annual seepage rates varied little with varying annual precipitation. Seepage losses were 1.5 to 3.2 times as great as evaporation losses. This research provides information on variability in seepage rates that will be valuable to regulatory personnel when writing new environmental regulations, and to engineers when designing new storage ponds and lagoons.*

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999b) Seepage characteristics and hydraulic properties of a feedlot runoff storage pond. Trans ASAE 42: 369 – 380. Retrieved from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1179&context=biosysengfacpub&sei-redir=1&referer=http%3A%2F%2Fscholar.google.com%2Fscholar%3Fq%3DSeepage%2Bcharacteristics%2Band%2Bhydraulic%2Bproperties%2Bof%2Ba%2Bfeedlot%2Brunoff%2Bstorage%2Bpond%26btnG%3D%26hl%3Den%26as_sdt%3D0%252C48%26as_vis%3D1#search=%22Seepage%20characteristics%20hydraulic%20properties%20feedlot%20runoff%20storage%20pond%22

Abstract: *Water and chemical transport were investigated beneath a 22-year-old beef feedlot runoff storage pond. Soil and sludge samples were collected from 14 borings to 6.1-m depths in a cross-section across the pond. The soils consisted of silt loam and clay loam, and the groundwater level was about 30 m beneath the land surface. Soil samples were analyzed for pH, NO_3-N, NH_4-N, Cl, P, K, SO_4-S, TKN, and organic matter. Physical and hydraulic properties were measured on undisturbed samples of soil and sludge to compare saturated hydraulic conductivity, moisture release characteristics, and bulk density. Saturated hydraulic conductivity measured in the laboratory ranged from 0.005 to 0.044 cm/day for the sludge and from 0.008 to 31.4 cm/day for the sidewall soil. The mean hydraulic conductivity values for the sludge and sidewall soil were not significantly different. Mean bulk densities were significantly different. The sludge exhibited high shrinkage when dried, and did not swell to its original volume when rewetted. Moisture content and chemical concentrations were higher beneath the sidewalls than beneath the pond bottom. A seepage rate of 0.87 cm/day was measured after a 7.6-cm rainfall event, following an extended dry period when the pond was empty. This short-term measurement exceeded the allowable seepage rate in Nebraska, however, seepage decreased with time following recharge of the sidewalls. Results have shown that water and chemical movement has occurred beneath the unlined feedlot runoff storage pond and that the plumes have traveled further than the maximum sampled depth of 6.1 m after 22 years of operation.*

Parker, D.B., Eisenhauer, D.E., Schulte, D.D. & Martin, D.L. (1999c) Seepage from earthen animal waste ponds and lagoons – An overview of research results and state regulations. Trans. ASAE 42: 485 – 493. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=1240129

Abstract: *Wastewater seepage from earthen animal waste lagoons and storage ponds can contaminate groundwater with nutrients and pathogens. For almost 30 years, the subject has been the focus of laboratory and field research projects designed to (I) measure if and how much earthen ponds and lagoons leak, (2) determine how different soil types affect seepage rates, and (3) evaluate the magnitudes and mechanisms of sealing from animal waste. In this article we present a research review performed to determine how researchers have attempted to answer these questions and how well they have been answered. We discuss weaknesses in the body of knowledge and present further research and educational needs. We also performed a review of 14 state regulations to assess and compare how different states govern seepage from ponds and lagoons. Six states regulate the maximum allowable seepage rate from ponds and lagoons (values ranging from 0.042 to 0.63 cm/day) while another six states regulate the maximum hydraulic conductivity of earthen liners (values ranging from 0.086 to 0.0086 cm/day). The two remaining states regulate neither. The results of this research and regulatory review demonstrate that there is still much to be learned about seepage from animal waste ponds and lagoons. We suggest that a risk-based approach to regulating seepage may be appropriate in the future.*

Parker, D.B., Rogers, W.J., McCullough, M.C., Cahoon, J.E., Rhoades, M.B. & Robinson, C. (2001). Infiltration characteristics of cracked clay soils in bottoms of feed yard playa catchments. Paper presented at: ASAE Annual International Meeting, Sacramento, CA. 29 July – 1 August, 2001. Paper 01-2281.

Abstract: *Randall clay (fine, smectitic, thermic Ustic Epiaquerts) is typical of the soils found in the bottom of playa lakes that are sometimes used as catchments for feedyard runoff in the Texas Panhandle. The objective of this research was to document the time-related sealing properties of cracked Randall Clay when subjected to a rapid infiltration event. Soil cores that were 7.6 cm in diameter by 15 cm deep were collected from two playa lakes in Randall County, Texas. The cores were air dried for one month, and cracking was documented using computer-aided tomography. The soil cores were subjected to infiltration and saturated hydraulic conductivity tests in a flexible wall permeameter. The modified Kostiakov equation was used to describe the infiltration characteristics of each soil core. Cumulative infiltration after 60 minutes varied from 0.15 to 1.60 cm, and the cores effectively sealed before water traveled more than 8 cm. These infiltration rates are lower than values reported in earlier research. Saturated hydraulic conductivities varied from 3.2 x 10 -4 to 7.2 x 10 -7 cm/min with geometric means of 4.1 x 10 -6 and 1.4 x 10 -5 cm/min at the two playas.*

Quade, D.J., Libra, R.D., & Siegley, L.S. (n.d.) Groundwater monitoring at an earthen manure-storage structure. Iowa Dept. of Natural Resources. Retrieved from http://www.igsb.uiowa.edu/Mapping/EMS/EMSGroundMon.htm

Introduction: *Groundwater quality has been monitored for two years in the immediate vicinity of three newly-constructed earthen manure storage (EMS) structures in Iowa. These structures are located in areas with differing surficial geologic materials: the Late Wisconsinan deposits of the Des Moines Lobe (DML), the Pre-Illinoian deposits of the Iowan Erosion Surface (IES), and the thick loess of western Iowa (WI). Three to seven shallow (<25 ft.) monitoring wells were installed around each structure. At two sites, wells were drilled through the berm structure on the downgradient side, while the third structure is ringed by a drainage tile that serves as a near-structure sampling point. Water levels are measured and water samples are collected monthly for nitrate-N, ammonium-N, fecal coliform bacteria, and chloride analysis. Samples are analyzed quarterly for total organic carbon, sulfate, phosphate, and other parameters. Liquid manure samples have been collected and analyzed from two of the three structures.*

Seepage has been detected at the DML and IES sites. Indications of seepage have been similar at all affected monitoring wells and include: the decline or disappearance of nitrate-N and sulfate, likely in response to the anaerobic nature of the liquid; and an increase in concentrations of chloride and total organic carbon. Chloride concentrations in the berm well at the DML site are 50% of those measured in the liquid waste and, at the IES site, chloride concentrations in the berm well are equal to those in the liquid waste. Concentrations of nutrients, such as ammonium-N, phosphorus, and potassium, have currently not increased, indicating these species are being adsorbed and retained on manure solids or the compacted soils at the base of the structures. Fecal coliform bacteria have been sporadically detected in the berm wells, but are not consistently transported from the structures. In this article, we will discuss the livestock waste handling system, the hydrogeologic setting, and the results from monitoring the effect of a Des Moines Lobe EMS structure on groundwater quality during its first two years of operation.

Reddi, L. and Davalos, H. (2000). Animal Waste Containment in Anaerobic Lagoons Lined with Compacted Clays. *Journal of Geotech. Geoenviron. Eng.*, 126(3), 257–264. Retrieved from http://ascelibrary.org/doi/abs/10.1061/(ASCE)1090-0241(2000)126:3(257)

Abstract: *The practice of animal waste containment has recently drawn much interest from public and regulatory agencies in agriculture-oriented states such as Kansas and North Carolina. In this paper, the debate surrounding the practice is outlined, and results from a research investigation pertinent to the state of Kansas are presented. The research investigation involved two phases. In the first phase, compacted specimens of Kansas soils were tested with animal waste as the influent. The key objective of this phase of research was to assess the range of seepage quantities and the transport characteristics of nitrogen in the ammonium form (NH_4-N) through the compacted soils. Results from this phase indicated a steady increase of microbial counts in the liquid effluent. However, biological clogging did not appear to be prominent during the NH_4-N breakthrough time period. The results indicate significant differences in microbial uptake of NH_4-N among samples of the same soil type. In the second phase, analytical and numerical solutions were used to simulate ammonium transport in the field-scale liners and to estimate upper-bound travel times and final concentrations of NH_4-N in the underlying soils. Results from this phase showed drastic differences in travel times and end concentrations of NH_4-N among liners prepared from the same soil type. The potential for significant retardation, decay, and saturation levels of NH_4-N in clay liners suggests that liner thickness is an important parameter. It is concluded that mass transfer characteristics of liner material, cation exchange capacity and microbial uptake in particular, should be important considerations in the design of animal waste lagoon liners.*

Ritter, W.F. & Chirnside, A.E.M. (1990) Impact of animal waste lagoons on ground-water quality. Biological Wastes 34(1): 39-54. doi.org/10.1016/0269-7483(90)90142-F. Retrieved from http://www.sciencedirect.com/science/article/pii/026974839090142F

Abstract*: Ground-water quality was monitored for three years at two sites around clay-lined animal waste lagoons on the Delmarva Peninsula. A swine waste lagoon located in an Evesboro loamy sand soil (excessively well-drained) was having a severe impact on ground-water quality. Ammonium nitrogen concentrations above 1000 mg/liter N have been measured in shallow monitoring wells around the lagoon. Chloride and total dissolved solids concentrations were also high. At the second site which has three lagoons and a settling pond in poorly drained soils, some seepage was occurring. Ammonium nitrogen, nitrate nitrogen, chloride and total dissolved solids were above background concentrations in some of the monitoring wells. There was a strong correlation between nitrate nitrogen and chloride concentrations in the monitoring wells. The results indicated that clay-lined animal waste lagoons located in sandy loam or loamy sand soils with high water tables may lead to degradation of ground-water quality.*

Rowsell, J.G., Miller, M.H. & Groenevelt, P.H. (1985) Self-sealing of earthen liquid manure storage ponds. 2. Rate and mechanisms of sealing. Journal of Environmental Quality. 14: 539 – 543. doi: 10.2134/jeq1985.00472425001400040014x. Retrieved from https://www.soils.org/publications/jeq/abstracts/14/4/JEQ0140040539?access=0&view=pdf

Abstract: *A laboratory study was conducted to determine the degree and rate of sealing of the soil surface where liquid beef (*Bos taurus*) manure with solids content of 50 g* kg^{-1} *was infiltrated into cores of a sandy loam, a loam, and a clay soil under hydraulic heads of 1 and 5 m. A second experiment explored the mechanism of sealing. The infiltration rate was expressed in the logarithmic form of the Kostiakov equation: log* q = A + b *log* t *where* q = *infiltration rate (m* s^{-1}*) and* t = *time (s). In this relation* A *represents the log of the initial infiltration rate (at 1.0 s) and* b *is the rate of change in rate with time on a logarithmic scale. The infiltration rate decreased rapidly with time and reached a value of* 10^{-8} *m* s^{-1} *or less within 30 d on all soils at 1-m hydraulic head. This rate is considered to indicate an essentially impermeable system. At a 5-m head the infiltration rate reached* 10^{-8} *m* s^{-1} *within 10 d on the clay soil but required periods > 30 d on the other two soils. A physical blocking of pores was the major mechanism of sealing. The rate of reduction of infiltration into the loam soil was similar for sterilized manure indicating that in this study biological activity was not a factor. Infiltration of a salt solution having similar cationic constituents as the manure remained constant over time indicating that dispersion of soil particles was not a factor.*

Sher, Y., Baram, S., Dahan, O., Ronen, Z. & Nejidat, A. (2012). Ammonia transformations and abundance of ammonia oxidizers in a clay soil underlying a manure pond. Federation of European Microbiological Societies. Microbiological Ecology. 81(1): 145 – 155. doi: 10.1111/j.1574-6941.2012.01347.x. Retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.1574-6941.2012.01347.x/abstract

Abstract: *Unlined manure ponds are constructed on clay soil worldwide to manage farm waste. Seepage of ammonia-rich liquor into underlying soil layers contributes to groundwater contamination by nitrate. To identify the possible processes that lead to the production of nitrate from ammonia in this oxygen-limited environment, we studied the diversity and abundance of ammonia-transforming microorganisms under an unlined manure pond. The numbers of ammonia-oxidizing bacteria and anammox bacteria were most abundant in the top of the soil profile and decreased significantly with depth (0.5 m), correlating with soil pore-water ammonia concentrations and soil ammonia concentrations, respectively. On the other hand, the numbers of ammonia-oxidizing archaea were relatively constant throughout the soil profile (*10^{7} *amoA copies per* g_{soil}*). Nitrite-oxidizing bacteria were detected mainly in the top 0.2 m. The results suggest that nitrate accumulation in the vadose zone under the manure pond could be the result of complete aerobic nitrification (ammonia oxidation to nitrate) and could exist as a byproduct of anammox activity. While the majority of the nitrogen was removed within the 0.5-m soil section, possibly by combined anammox and heterotrophic denitrification, a fraction of the produced nitrate leached into the groundwater.*

Simpkins, W.W. & Burkart, M.R. (2002) Hydrogeologic settings of earthen waste storage structures associated with confined animal feeding operations in Iowa. Proceedings – Waste Technology. Retrieved from http://www.engg.ksu.edu/HSRC/ag/2002/proceed/b02.pdf

Abstract: *Thirty-four permitted earthen waste storage structures (EWSS) were investigated to characterize their hydrogeologic setting using digital soils data, digital elevation data, geologic maps, and oblique aerial photographs. Nearly 18 percent of the sites were constructed above alluvial aquifers and on flood plains. More than half of the area within 3.2 km of most sites had soils with a vertical permeability = 25.4 mm/hr. and well or moderately to well-drained soils. The prevalence of EWSS depths exceeding 3 m and areas with water table less than 1.6 m deep suggests that most sites are below the water table. Ephemeral or perennial streams were found within 152 m at one-third of the sites. Risks to water resources may be reduced by using siting criteria that incorporate geologic, hydrogeologic, and soils data. Controlling the timing of manure application and avoiding application on frequently flooded and permeable soils may reduce the risk of water-resource contamination. Application of well-established, scientifically defensible ground-water monitoring techniques should be used to locate the position of the water table during construction and throughout the life of the EWSS. Uniform stream setbacks may not be appropriate for all hydrogeologic settings. These considerations, used with appropriate performance standards, would reduce the potential for contamination of water resources.*

Singleton, M.J., Esser, B.K., Moran, J.E., Hudson, G.B., McNab, W.W. & Harter, T. (2007). Saturated zone denitrification: Potential for natural attenuation of nitrate contamination in shallow groundwater under dairy operations. Environmental Science Technology. 41:759-765. doi:10.1021/es061253g. Retrieved from http://pubs.acs.org/doi/abs/10.1021/es061253g

Abstract: *We present results from field studies at two central California dairies that demonstrate the prevalence of saturated-zone denitrification in shallow groundwater with $^{3}H/^{3}He$ apparent ages of <35 years. Concentrated animal feeding operations are suspected to be major contributors of nitrate to groundwater, but saturated zone denitrification could mitigate their impact to groundwater quality. Denitrification is identified and quantified using N and O stable isotope compositions of nitrate coupled with measurements of excess N_2 and residual NO_3^- concentrations. Nitrate in dairy groundwater from this study has $\delta^{15}N$ values (4.3−61‰), and $\delta^{18}O$ values (−4.5−24.5‰) that plot with $\delta^{18}O/\delta^{15}N$ slopes of 0.47−0.66, consistent with denitrification. Noble gas mass spectrometry is used to quantify recharge temperature and excess air content. Dissolved N_2 is found at concentrations well above those expected for equilibrium with air or incorporation of excess air, consistent with reduction of nitrate to N_2. Fractionation factors for nitrogen and oxygen isotopes in nitrate appear to be highly variable at a dairy site where denitrification is found in a laterally extensive anoxic zone 5 m below the water table, and at a second dairy site where denitrification occurs near the water table and is strongly influenced by localized lagoon seepage.*

Tyner, J.S., & Lee, J. (2004) Influence of seal and liner hydraulic properties on the seepage rate from animal waste holding ponds and lagoons. Trans. ASAE 47:1739 – 1745. Retrieved from

http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

A recent study presented a two-layer (liner and seal) unsaturated model to predict the flux from lagoons. The model predicted that flux is not related to liner thickness, is only weakly related to the saturated hydraulic conductivity of the liner, and is primarily controlled by the hydraulic conductivity of the seal. In this study, we evaluated those predictions by monitoring the flux of dairy waste through eight intact soil monoliths (silt loam) with large macropores. After applying a 2.3 m column of dairy waste (2.3% total solids) to the top of the monoliths, a seal developed within 2 d, and the leakage continued to decrease for the remaining 83 d of the test. The average leakage rate after 85 d was 0.70 mm d−1, and an average of 218 mm of waste infiltrated into the monoliths. Small holes drilled into the sides of the monoliths, just below the soil surface, failed to fill with liquid, which demonstrated that the soil was unsaturated and therefore was not limiting the leakage rate. The amount of waste required to initially seal the monoliths did not correlate to the seal growth rate, which also implies that the soil contributed little to the seal growth rate or leakage rate after seal development. A plot of cumulative waste infiltration versus the square root of time showed a strong linear relationship (R2 = 0.996), which suggests that the phenomenon of dairy waste sealing a soil is analogous to filter cake growth. Long-term studies with other soil and waste types are needed to confirm the findings of this research. From https://sites.google.com/site/johnstyner/leakagefromanimalwasteholdingponds

Tyner, J.S., Wright, W.C., & Lee, J. (2006) Lagoon sealing and filter cakes. Trans. ASAE 49:527 – 531. Retrieved from http://scholar.google.com/scholar?q=Influence+of+seal+and+liner+hydraulic+properties+on+the+seepage+rate+from+animal+waste+holding+ponds+and+lagoons&btnG=&hl=en&as_sdt=0%2C48&as_vis=1

Abstract: *Animal waste holding ponds and lagoons are often lined with soil and may leak leachate into the underlying media. Calculating the flux of leachate through a pond liner is typically predicted by applying Darcy's law across the liner while assuming saturated conditions. The formation of a thin sealing layer atop holding pond liners is common due to the abundance of fines and organic material within animal waste. Research has shown that these seals are credited with reducing the flux from holding ponds by one or more orders of magnitude due to the very low hydraulic conductivity of the sealing layer. Because even compacted clay liners are likely to have hydraulic conductivities much larger than the overlying seal, a unit gradient forms within the liner such that it desaturates to the point that its unsaturated hydraulic conductivity is equal to the flux, a process similar to that of water infiltrating into a crusted soil. In this study, a two−layer (liner and seal) unsaturated model is presented for describing the flux of animal waste from holding ponds. The two−layer model predicts that flux is not a function of liner thickness, and is only a weak function of liner hydraulic conductivity. Instead, flux through the liner is primarily a function of seal hydraulic conductivity, seal thickness, and depth of waste. The van Genuchten−Mualem hydraulic parameters (alpha and n) of the liner are found to correlate well with flux, but the saturated hydraulic conductivity of the liner is found to be a poor predictor of flux.* From https://sites.google.com/site/johnstyner/leakagefromanimalwasteholdingponds

Van der Schans, M.L., Harter, T., Leijnse, A., Mathews, M.C., & Meyer, R.D. (2009) Characterizing sources of nitrate leaching from an irrigated dairy farm in Merced County, California. Journal of Contaminant Hydrology. 110(1-2): 9 - 21. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169772209000862

Abstract: *Dairy farms comprise a complex landscape of groundwater pollution sources. The objective of our work is to develop a method to quantify nitrate leaching to shallow groundwater from different management units at dairy farms. Total nitrate loads are determined by the sequential calibration of a sub-regional scale and a farm-scale three-dimensional groundwater flow and transport model using observations at different spatial scales. These observations include local measurements of groundwater heads and nitrate concentrations in an extensive monitoring well network, providing data at a scale of a few meters and measurements of discharge rates and nitrate concentrations in a tile-drain network, providing data integrated across multiple farms. The various measurement scales are different from the spatial scales of the calibration parameters, which are the recharge and nitrogen leaching rates from individual management units. The calibration procedure offers a conceptual framework for using field measurements at different spatial scales to estimate recharge N concentrations at the management unit scale. It provides a map of spatially varying dairy farming impact on groundwater nitrogen. The method is applied to a dairy farm located in a relatively vulnerable hydrogeologic region in California. Potential sources within the dairy farm are divided into three categories, representing different manure management units: animal exercise yards and feeding areas (corrals), liquid manure holding ponds, and manure irrigated forage fields. Estimated average nitrogen leaching is 872 kg/ha/year, 807 kg/ha/year and 486 kg/ha/year for corrals, ponds and fields respectively. Results are applied to evaluate the accuracy of nitrogen mass balances often used by regulatory agencies to assess groundwater impacts. Calibrated leaching rates compare favorably to field and farm scale nitrogen mass balances. These data and interpretations provide a basis for developing improved management strategies.*

Westerman, P.W., Huffman, J.S., & Feng, J.S. (1995) Swine lagoon seepage in sandy soil. Transactions of the ASABE. 38(6): 1749-1760. Abstract retrieved from https://elibrary.asabe.org/abstract.asp?aid=28002&t=2&redir=&redirType=

Abstract: *Swine manure anaerobic lagoons have sometimes been constructed in sandy soil without clay liners. Although swine manure and other animal manures have been reported to physically "seal" lagoons to various degrees, long-term studies with sandy soil have been lacking. Two swine manure, anaerobic lagoons located in sandy, coastal plain soil were investigated. Both continued to have significant seepage after 3.5 to 5 years of receiving waste. Monitoring wells indicated broad seepage plumes, and much variation in concentrations of several parameters with well location, time, and depth of well. The variations indicate the difficulty of accurately monitoring and quantifying seepage transport of nutrients, and the complexity of developing groundwater transport models to accurately predict transport and transformations of chemical compounds, particularly ammonium and nitrate nitrogen, at various distances from the lagoon.*

White, I. & Denmead, O.T. (1989) Point and whole basin estimates of seepage and evaporation losses from a saline groundwater-disposal basin. Hydrology and Water Resources Symposium 1989: Comparisons in Australian Hydrology: Preprints of papers. Abstract retrieved from http://search.informit.com.au/documentSummary;dn=484307596156300;res=IELENG

Abstract: *Rapid point and whole basin techniques are described for estimating seepage and evaporation losses from groundwater disposal and evaporation ponds. Floating capillary-scale seepage meters, water depth monitoring, salt balance, and the aerodynamic, eddy correlation and bulk transfer coefficient methods were employed in a study of a 20 ha basin. Both point and whole basin estimates indicate seepage rates of less than 0.2 mm d-l. Nearly 40% of the evaporation from the basin occurred at night due to heat stored in the water. Evaporation was close to 0.7 times the class A pan evaporation over the study period, which is consistent with the local advective situation.*

Withers, P.J.A., McDonald, H.G., Smith, K.A., & Chumbley, C.G. (1998). Behavior and impact of cow slurry beneath a storage lagoon: I. 49. doi:10.1023/A:1004923631734. Retrieved from http://link.springer.com/article/10.1023%2FA%3A1004923631734?LI=true#page-1

Abstract: *The chemical and biological composition of groundwater sampled from a 76 m deep borehole situated 80 m from an unlined, earth-banked lagoon excavated in Upper Chalk and continuously used to store liquid cow manure was regularly monitored from August 1975 to January 1982 for signs of pollution. The lagoon became self-sealing 3 months after the start of filling in 1975, but was further enlarged and re-filled in autumn 1976, and emptied by dragline in September 1978 and 1980. No significant changes in groundwater composition were detected in the period August 1975 to December 1978. In January 1979, significant numbers of Escherichia coli and a large, rapid increase in concentrations of ammonium-nitrogen (NH_4-N), phosphorus (P), potassium (K), sodium (Na), chloride (Cl) and sulphate (SO4) were detected in the groundwater. Nutrient concentrations fluctuated at elevated levels throughout 1979 but decreased during 1980. Additional bacterial and chemical (NH_4-N, P and K) contamination was recorded in January 1981 and subsequent months. The contamination was considered to have occurred as a result of fissure flow through the unsaturated zone of the Upper Chalk following repeated disruption of the self-sealing layer during emptying of the lagoon by dragline in September 1978 and 1980. The results indicate that unlined, earth-banked slurry storage lagoons need to be carefully managed to avoid biological and chemical pollution of Chalk aquifers.*