Davis, CA
February 3, 1995

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CENTRAL COAST WATER QUALITY CONTROL BOARD
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81 Higuera, Ste. 200
San Luis Obispo 93401-5427

Sorrel Marks
Sanitary Engineering Associate
California Regional Water Quality
Control Board
Central Coast Region
81 Higuera Street, Suite 200
San Luis Obispo, CA 93401-5427

Dear Ms. Marks:

Please find enclosed my written evaluation of the Los Osos Soil and Groundwater Nitrate Study. I have also provided brief comments on Jay Cano's and Clinton Milne's letters. I hope these comments are useful in the Board's deliberations.

I have also attached a one-page curriculum vitae and my publication list for your information.

Sincerely,

Dennis E. Rolston

Dennis E. Rolston
Professor

ATTACHMENT 2

Evaluation of Los Osos Soil and Groundwater Nitrate Study

Dennis E. Rolston, Professor
Land, Air and Water Resources
University of California
Davis, CA 95616

The TAC has made a determined effort to make some sense from a limited data set of N concentrations beneath disposal pits and leach lines in the Los Osos area. It is obvious that a large amount of work went into trying to understand the nitrogen transport and transformation processes under septic systems. My criticism is not of the report or the work of the committee but of the less-than-adequate data available to the committee.

The use of suction lysimeters allow for collection of solute concentration in the soil water as a function of time. If the process to be studied is expected to exhibit considerable variable in time, lysimeters are a good sampling device. However, if the process of interest is highly variable in space, it is best to take many more spatial samples. I expect that nitrogen concentrations in the soil solution below septic systems may vary more in space than in time. The release of effluent from septic systems is more or less continuous and constant with no extraordinarily large inputs and then long periods of no effluent. Thus, once the septic system has been in operation for awhile, a quasi steady state should be established which would not change much in time. However, the distribution of effluent from leach pits or leach lines may be very variable as a result of unequal application of effluent into the bottom of the leach pit or along the leach line. Placement of suction lysimeters or removal of soil samples spaced only a few inches apart may result in very different values for dissolved solute in soil.

It is well established in the scientific literature that the leaching of solutes in soil water is an extremely variable process due to natural heterogeneity of the soil and underlying geological sediments. For example, it is common for solute from a uniform application at the soil surface to reach a deeper suction lysimeter in a shorter time than for that of a shallower lysimeter placed only a few inches away. Solute follows flow lines (stream tubes) with very different velocities from location to location. Most field experiments, even from uniform application of solutes, require many replications of lysimeters at each depth in order to capture some of this inherent variability of solute leaching. The attempt to place the lysimeters above each other at the various depths, as was the goal for the Los Osos leach pits, does not necessarily guarantee that every lysimeter will be within the same stream tube. For the leach line study, the lysimeters were installed vertically and not on an angle, so the potential of the lysimeters being in different stream tubes is very possible. The point of all the above is that data collected with only one replication (one sampler at each depth) for each of the three systems may be highly uncertain and unreliable. I expect that results from only one replication of solute concentration from lysimeters of a field experiment would not be acceptable for publication in any scientific journal. Thus, I believe that the TAC committee has made some fairly strong conclusions based upon a potentially unreliable or misleading data set. Nothing short of several replications at each depth of all three sites will be needed to confirm the processes suggested in the TAC report.

The report suggests that a significant amount of denitrification occurred below the leach pits and lines of the three locations. For the Bayridege Estates site, I believe that vertical placement of lysimeters, particularly with only one replication, greatly complicates the interpretation of results. If samples from the 13th St site are really representative, some denitrification is suggested. However, the increasing nitrate concentrations at the 40 ft depth suggest that differences in nitrate leaching due to spatial heterogeneity makes this suggestion of apparent denitrification questionable. The data for the 14th St site appear to give a stronger suggestion of significant denitrification. Again, if these data are truly representative, and not just an artifact of a single sampling, some denitrification seems to be occurring under this site. I believe that there are still many unanswered questions concerning how anaerobic conditions developed deep within the profile as discussed later on in this evaluation. A bigger question is whether this site is in any way representative of the majority of systems in the Los Osos area and whether the amount of denitrification occurring is sufficient to conclude that septic systems are not causing a significant impairment of groundwater quality.

I have several comments and questions on specific parts of the report which I will attempt to address one by one in the sections to follow:

<u>Letter to Board of Supervisors dated July 7, 1994</u>

p 1, 2nd parag. from bottom. The data from one replication of samplers suggest that denitrification may be occurring. The question is whether these observations are really representative of the area and whether it is enough to reduce nitrate input to the groundwater to low enough loadings to protect groundwater quality.

p 2, parag. 3. The fact that several sites were abandoned due to high water table conditions suggests that sites like these could result in a direct input of nitrogen as ammonium into the groundwater. If there is not sufficient aeration at the bottom of the leach pits or leach lines for nitrification to occur rapidly, ammonium may be moving into the groundwater and slowly being nitrified in the groundwater.

p 2, 2nd parag. from bottom. Although there may be a reasonably large nitrogen pool in the soil of Ceanothus stands, this nitrogen is mostly in the organic form. The rate of mineralization of this pool to inorganic forms and subsequent leaching below the root zone is the question that needs to be addressed in order to determine if this is another possible source of contamination or not.

Main study report

p 16, bottom. Neutron probes measure soil-water content not soil-water movement.

Table 3. For the 13th and 14th St sites, water contents appear to be about the same from the surface all the way to the water table. Since the soil coring was done on an angle, some of the upper samples should have been outside the influence of water leaching below the leach pit. Why didn't the soil sampling intercept a wetter area under the leach pit. Either the whole area was equally wet, or the sampling did not intercept the zone where effluent leaches below the pit. Similarly, why wasn't there more ammonium measured at the 15-16.5 ft depth, particularly for the 13th St site? It appears that the soil sampling may have missed the region where N was leaching below the pit. There is a slight increase in ammonium concentration at that depth for the 14th St site. However, it again raises the question about spatial variability of leaching below the pits.

Nitrite was low and pH about neutral, so chemodenitrification shouldn't be too large. For the Bayridge Estate site, it is apparent that chloride was increasing with depth which complicates using the nitrate/chloride ratio.

p 23, last paragraph. The report suggests that the deeper samples may be in error due to bubbling in the lysimeter. It is not clear how this can occur. If the air was coming from inside the lysimeter, it was most likely at a relative humidity of 100%. Thus, there should be no evaporation from bubbling air through the sample. Later on the next page, the statement is made that the liquid sample was forced to the surface by pressure. Again, where does dry air come from which would evaporate some of the liquid sample?

Fig. 13. Were the measured concentrations really equal with depth?

Table 5. How was ammonium concentration obtained at the bottom of the leach pit? Was it sampled directly or assumed to be the same

as in the septic tank? What about nitrification occurring between the tank and the bottom of the pit? Also, the EC/chloride ratios are not constant.

Fig. 19. For the water content graph, if the bulk density is assumed to be 1.8 for this soil (couldn't find a measurement anywhere), there was still about 10% air-filled pore space at 19 ft. Thus, the soil was not saturated at this depth.

p 46, parag. 2. The 13th St site may not have been anywhere near a steady-state condition due to the system being in operation for only five months prior to initiation of measurements and to pumping effluent from the tank at periodic intervals. Data from a transient state system will be more difficult to interpret.

Table 6. Same question on how ammonium was measured at the bottom of the leach pit. For the 14th St site, the EC and Cl are definitely not constant with depth and the EC/Cl ratios change very drastically with depth. Why is this happening? This causes problems in interpreting the nitrate/chloride ratio and again raises questions about heterogeneity of solute transport.

p 47, 1st paragraph. Does the total N to chloride ratio remain constant in time in the effluent from the septic tank? To use the nitrate/chloride ratio as an indicator of denitrification, one must assume that this ratio does not change with time in the effluent from the septic tank.

p 47, last parag. The units should be 82 mg N/kg soil, not mg N/L. It should be higher than soil solution since it would also include organic N.

Fig. 22. I expect that the data from the Bayridege Estates site would be quite variable and uncertain. The lysimeters were installed vertically at some unknown distance between two leach lines. Thus, they are likely sampling different parts of the profile as discussed in the opening statement. In addition, substantial downward and horizontal movement of the plume must occur before the moving N intercepts the lysimeters. This could give misleading results. Salinity also changes with depth which could be due to the same phenomena.

p 58. What happened to Figs. 23, 24, 26, and 27?

p 58, There appears to be significant ammonium in the soil solution for the Bayridge site. This may imply that there is significant movement of N as ammonium to the groundwater.

p 59, last parag. I agree that there may be a large organic N pool in the soil below the native site. However, the question that needs to be answered is how fast this pool is being mineralized to an inorganic form and is the inorganic form available for leaching? Whether this contributes significantly to the nitrate loading in the groundwater is purely speculative at this time without measurements.

p 61, 5th parag. Although the gamma ray logs suggest that there may be clay layers or something else in the deeper part of the profile, the water content measured by neutron probe and from the soil samples don't seem to indicate areas of higher water content which could be indicative of higher clay layers.

p 62, 2nd parag. from bottom. As discussed earlier, the soil appears to be unsaturated at 19 ft.

p 63, 2nd parag. Unless the bulk density is much greater than 1.8, the water content data do not show evidence of saturated conditions or a perched water table.

p 65, 8.51 Nitrogen transformations. Aerobic conditions must have existed between the 15-20 ft depth in order for nitrification to occur rapidly. The data suggest than denitrification occurred below that depth to remove some of the nitrate from the soil solution. The report implies that there must have been a rapid decrease in oxygen level between about the 25-30 ft depth in order to create sufficient anaerobic conditions for denitrification. It was suggested that the development of anaerobic conditions at the deeper depths was due to movement of organic carbon from the leach pit. If this is the mechanism, I can't understand how the carbon could move through the 15-20 ft depth without causing anaerobic conditions to develop in that zone as well. What causes the hypothesized lack of oxygen between 25 and 30 ft? For denitrification to occur, there must be a supply of nitrate and organic carbon, and there must be the development of anaerobic conditions at least in pockets or localized regions within the soil. Without some evidence that anaerobic conditions could have developed, it is difficult to understand how such a large amount of biological denitrification could have occurred. The pH was low for a few samples in one of the sites. Maybe chemodenitrification should be considered. Without more replications, the elucidation of the mechanisms is highly problematic.

p 67, top. The only way that nitrate concentrations could increase again with depth is if there was a source producing nitrate. The report implies that ammonium leached to 40 ft. Table 5 shows basically no ammonium anywhere in the profile below 15 ft. The more likely explanation is variability of sampling in space. Again, one replication is not sufficient.

p. 67, parag. 3. The report tries to provide an explanation for changing EC with depth. Again, variability in sampling in space could easily result in the differences observed. Another explanation could be that salt inputs to the septic system were not constant in the past causing different concentrations as the solute moves through the soil. Again, there is not enough data to be confident of the process.

p. 72, 2nd parag. from bottom. Same possible reason as above.

p. 73, 2nd parag. from bottom. On p 24, it was stated that the liquid sample was forced to the surface by positive air pressure and not by vacuum. There should not be bubbling of air through the sample. I don't understand where the bubbles come from.

p 74, top. If nitrate concentrations below the 25 ft depth are considered uncertain, a similar uncertainty should also apply to the shallower depths.

p 74, 3rd parag. There is no reason to expect that chloride concentration in groundwater would be the same in the vadose zone above groundwater.

p 76, There is a lot of speculation here in terms of development of aerobic and anaerobic conditions.

Rolston's comments on Jay Cano's memo dated October 24, 1994

General Comments

Certainly, not all of the nitrate is lost (denitrified) under the leach pits and leach lines. The data suggest that denitrification may be occurring but not to such a large rate as to completely remove all nitrate. I agree that further studies would be required to substantiate the degree that denitrification may be occurring and decreasing the nitrogen loading to groundwater.

Cano suggests that dispersion or lateral spreading could cause decrease in nitrate concentrations which could be interpreted as denitrification. The leachate will not move absolutely vertically and some lateral spreading will occur. Lateral spreading should be less in sands than in more clayey material. The affect of lateral spreading on the measured nitrate concentration would depend upon whether the lysimeters happened to be on the edge of the plume or directly in the middle of the plume. The width of the plume in the soil may be quite variable. Although the top of the leach pits are apparently about 14 ft wide, they appear to narrow to something much less than that. The plume at the bottom of the pit in the gravel could be quite narrow. If there was information that the nitrogen/chloride ratio in the septic tank effluent remained constant in time and if the soil had a low and uniform chloride concentration, using the nitrate/chloride ratio would take out the effect of any dilution due to lateral spreading. Unfortunately, without data, I doubt if these conditions were satisfied. In fact, there is evidence that EC and chloride were not constant with depth.

I am not sure about the possibility of ammonia volatilization during vacuum extraction of soil solution. Certainly if there was a significant amount of dissolved ammonia gas in the soil solution, extracting the solution under vacuum would volatilize the ammonia. The chemical equilibrium between ammonium and ammonia is highly pH dependent. One would need to do some chemical equilibria calculations to determine if the possibility of ammonia volatilization during vacuum extraction might occur or not.

I agree that the interpretations from the nitrate/chloride ratio are somewhat tenuous due to the uncertainty of the background soil chloride concentrations and the chloride in the septic effluent.

Specific Comments

Item 11. I agree that the placement of the vertical lysimeters somewhere beside the leach lines may result in misleading data.

Item 23. Some horizontal spreading of the leachate is likely. There is nothing in the data that can confirm this one way or the other.

Item 31. The very transient nature of the effluent applications greatly complicates interpretation. Also, sample locations and sampling intensity may not have been sufficient to capture the transient behavior of the leachate.

Item 38. For very shallow groundwater, ammonium may not be nitrified. Thus, with the low CEC sandy soils, ammonium may leach directly into groundwater.

Item 39. One reason why denitrification could be higher under septic systems is that there may be more soluble organic carbon which can leach into the soil below the effluent discharge point than for native soils. Data are available showing movement of soluble organic carbon below high applications of animal manure to land. As far as I know, data are not available below septic systems.

Item 50. It would be interesting to estimate the amount of water recharge to the groundwater from septic systems compared to natural recharge. Then, the relevance of the nitrate concentration in the soil water of the unsaturated zone could be put more into perspective.

Rolston's comments on Clinton Milne's letter dated August 9, 1994

p 2, item 2. This is an important point. The three test sites may not be representative of the entire area. Also, the septic systems in the high water table areas may be leaching ammonium directly into groundwater.

p D-1,5; 2nd parag. I agree that the number of tests conducted was minimal and that the three instrumented sites appear to have been located in ideal locations.

p D-1,5; 4th parag. It is clear from the data that nitrates were not reduced to zero.

p D-1,6; 2nd parag. from bottom. This is a good point stating that nitrates are not the sole problem. Besides the systems not functioning properly during high water table periods, I would think that there also must be a danger of bacteria, viruses, etc. moving into the groundwater.

ID to Charge: 7779

FAX

Number of pages sent, including this cover sheet: 1

CENTRAL COAST REGIONAL WATER QUALITY CONTROL BOARD
RECEIVED
FEB 16 1995
81 Higuera, Ste. 200
San Luis Obispo 93401-5427
California

DATE: February 16, 1995

TO: Sorrel Marks

FROM: Dennis Rolston Dennis S Rolston

FAX NO: 805-543-0397

MESSAGE:

In terms of the Los Osos nitrate groundwater issue, I would like to point out another bit of evidence that might be useful to you and the Board.

In digging through some files the other day, I came across a copy of a letter from Roy Spalding of Nebraska to Percy Garcia dated August 31, 1987 concerning analysis of nitrogen isotopes in some groundwater samples from Los Osos. I believe that Angela Carpenter must have passed this on to me sometime. In this letter, Roy concludes that the majority of nitrate was from some mixed source but that septic tank leachate contribution was probably small. I believe that Roy came to that conclusion because he thought that the del N-15 from human waste should be greater than +10. The report that Fogg and I submitted to the State and Central Coast Boards last year, however, shows that the del N-15 from septic leach lines and pits from a location near Davis and in the Salinas Valley ranged between +5 and +10 with a mean of +8.2. The samples from Los Osos had del N-15 values ranging between +6 and +10 with means of +8 on one sampling date and +7.8 on another sampling date. Thus, you can see that the del N-15 values of nitrate from Los Osos groundwater are very close to measured values below septic tank leachate sources in our report. Thus, I disagree with Spalding and believe that the data do indeed point to septic tank effluent as a primary source of nitrate in groundwater in Los Osos.

In my opinion, there are three ways that del N-15 values can be in the range of +6 to +10. One is from septic tank effluent as I already described above. Another is if there is a mixture of nitrate from fertilizer and/or natural sources and from animal waste. Fertilizer and natural soil organic matter sources from our report range between 0 and +5 with a mean of about +2.6. Animal sources range between about +6 to +34 with a mean of +13. Nitrate from nitrogen-fixing plants would tend to be slightly negative. Other sources could be geologic nitrate from alluvial sediments. We have analyzed some samples of geologic sources from the east side of the Coast Range and came up with values in the same range as fertilizer and natural soil organic matter. In personal communication with Professor Lanny Lund at UC Riverside, they have found that one geologic source of nitrate gave del N-15 values in the very negative range. Thus, it does not appear that nitrate in the groundwater from Los Osos could be from geologic sources unless mixed with a high loading from some kind of animal source. Thus, without the presence of animal sources such as feedlots, dairies, or large manure applications to land, the del N-15 values tend to point toward septic tank effluent.

A third way that del N-15 values could be in the +6 to +10 range is if there was significant denitrification of nitrate from a natural or fertilizer source. Denitrification of septic tank effluent would tend to drive the del N-15 values higher than the +6 to +10 range. To move del N-15 values from about +2.5 to +8 would require that denitrification of the native or fertilizer N below the root zone of crops was in the order of 20%. From our investigations of fertilizer and natural soil organic matter sources near Davis and in the Salinas Valley, we saw no evidence of denitrification within the vadose zone anywhere near this magnitude. Thus, I believe that it is highly unlikely that denitrification from natural or fertilizer sources could be the cause of the del N-15 of nitrate in the groundwater to be in the +6 to +10 range.

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Education:

B.S., Agricultural Science, South Dakota State University, Brookings (1965)

M.S., Soil Physics, Iowa State University, Ames (1967)

Ph.D., Soil Science, University of California, Davis (1971)

Work Experience:

1968-1971, Staff Research Associate IV, University of California, Davis

1971-1977, Assistant Professor and Assistant Soil Physicist, University of California, Davis

January 1971 - August 1972, Technical Advisor at Water Technology Center, New Delhi, India

1977-1981, Associate Professor and Associate Soil Physicist, University of California, Davis

1978-1979, Visiting Associate Professor, University of Florida, Gainesville

1981-1986, Associate Dean of Resource Sciences and Engineering, College of Agricultural and Environmental Sciences.

1981-Present, Professor of Soil Science and Soil Physicist, University of California, Davis

1986-1987, Visiting Professor, University of Guelph, Guelph, Ontario, Canada

1991-1993, Associate Chair, Soils and Biogeochemistry, LAWR

1992-Present, Director, Center for Ecological Health Research

Professional activities:

Reviewer for several Journals and granting agencies

Extramural grants from the Kearney Foundation, Water Resources Control Board, U.C. Toxics Substances Program, USDA, NIEHS, EPA, USGS

Member of several Scientific Societies

Fellow, Soil Science Society of America

Fellow, American Society of Agronomy

Past chair (1988), Soil Physics division of Soil Science Society of America.

Chair of Faculty (1990-91), College of Agricultural and Environmental Sciences.

Consulting editor, Soil Science

Teaching and advising:

Soil Science 107 - An undergraduate course on the principles of soil physics

Soil Science 207 - A graduate class on transport processes in soils

Research program:

The research program is directed at understanding the mechanisms of transport and transformation of water, salt, nutrients, contaminants and gases in soil. Interest in soil gases involve diffusion of nitrous oxide and dinitrogen gases produced during denitrification and transport and transformation of volatile organic compounds in the unsaturated zone. More than 95 referred publications.

PUBLICATIONS

D. E. Rolston

1. Rolston, D.E. and M.L. Horton. July-August 1968. Two beta sources compared for evaluating water status of plants. Agronomy Journal 60:333-336.

2. Rolston, D.E., D. Kirkham, and D.R. Nielsen. July-August 1969. Miscible displacement of gases through soil columns. Soil Science Society of America Proceedings 33(4):488-492.

3. Rolston, D.E., D.R. Nielsen, and J.W. Biggar. November 1971. Miscible displacement of ammonia in soil; determining sorption isotherms. Soil Science Society of America Proceedings 35:899-905.

4. Rolston, D.E., D.R. Nielsen, and J. Biggar. November 1972. Desorption of ammonia from soil during displacement. Soil Science Society of America Proceedings 36:905-911.

5. Obrigewitsch, R.P., D.E. Rolston, D.R. Nielsen, and F.S. Nakayama. September-October 1975. Estimating relative leaf water content with a simple beta gauge calibration. Agronomy Journal 67:729-732.

6. Rolston, D.E., R.S. Rauschkolb, and D.L. Hoffman. November-December 1975. Infiltration of organic phosphate compounds in soil. Soil Science Society of America Proceedings 39(6):1089-1094.

7. Rolston, D.E., S. Singh, and C. Dakshinamurti. 1976. Evaluation of field methods for measuring or predicting soil-water properties. Journal of Indian Society of Soil Science 24(2):101-113.

8. Rauschkolb, R.S., D.E. Rolston, R.J. Miller, A.B. Carlton, and R.G. Burau. January-February 1976. Phosphorus fertilization with drip irrigation. Soil Science Society of America Journal 40(1):68-72.

9. Rolston, D.E., M. Fried, and D.A. Goldhamer. March-April 1976. Denitrification measured directly from nitrogen and nitrous oxide gas fluxes. Soil Science Society of America Journal 40(2):259-266.

10. Delwiche, C.C. and D.E. Rolston. March-April 1976. Measurement of small nitrous oxide concentrations by gas chromatography. Soil Science Society of America Journal 40(2):324-327.

11. Rolston, D.E. and M.A. Mariño. November-December 1976. Simultaneous transport of nitrate and gaseous denitrification products in soil. Soil Science Society of America Journal 40(6):860-865.

12. Rolston, D.E. and B.D. Brown. May-June 1976. Measurement of soil gaseous diffusion coefficients by a transient-state method with a time- dependent surface condition. Soil Science Society of America Journal 41(3):499-505.

13. Peacock, W.L., D.E. Rolston, F.K. Aljibury and R.S. Rauschkolb. 1977. Evaluating drip, flood, and sprinkler irrigation of wine grapes. American Journal of Enology and Viticulture 28(4):193-195. January.

14. Castro, C.L. and D.E. Rolston. 1977. Organic phosphate transport and hydrolysis in soil: Theoretical and experimental evaluation. Soil Science Society of America Journal 41(6):1085-1092.

15. Rolston, D.E. 1978. Application of gaseous-diffusion theory to measurement of denitrification. In: Nitrogen in the environment. Nitrogen behavior in field soil. D. R. Nielsen and J. G. MacDonald (eds.), Academic Press, New York 1:309-335.

16. Rolston, D.E., D.L. Hoffman, and D.W. Toy. November 1978. Field measurement of denitrification: I. Flux of N_2 and N_2O. Soil Science Society of America Journal 42(6):863-869.

17. Rolston, D.E., R.S. Rauschkolb, C.J. Phene, R.J. Miller, K. Uriu, R.M. Carlson, D.W. Henderson. August 1979. Applying nutrients and other chemicals to trickle-irrigated crops. Division of Agricultural Sciences, University of California Bulletin 1893. 14 pages.

18. Rolston, D.E., F.E. Broadbent, and D.A. Goldhamer. February 1979. Field measurement of denitrification: II. Mass balance and sampling uncertainty. Soil Science Society of America Journal 43:703-708.

19. Hoffman D.L. and D.E. Rolston. January-February 1980. Transport of organic phosphate in soil as affected by soil type. Soil Science Society of America Journal 44(1):46-52.

20. Rao, P.S.C., R.E. Jessup, D.E. Rolston, J. M. Davidson, and D.P. Kilcrease. July 1980. Experimental and mathematical description of nonadsorbed solute transfer by diffusion in spherical aggregates. Soil Science Society of America Journal 44(4):684-688.

21. Brown, B.D. and D.E. Rolston. August 1980. Transport and transformation of methyl bromide in soils. Soil Science 130(2):68-75.

22. Rao, P.S.C., D.E. Rolston, R.E. Jessup and J.M. Davidson. November 1980. Solute transport in aggregated porous media: Theoretical and experimental evaluation. Soil Science Society of America Journal 44(6):1139-1146.

23. Rolston, D.E. 1981. Nitrous oxide and nitrogen gas production in fertilizer loss. pp. 127-149. In: C. C. Delwiche, (ed.). Denitrification, nitrification and atmospheric nitrous oxide, John Wiley & Sons, Inc., New York.

24. Miller, R.J., D.E. Rolston, R.S. Rauschkolb, and D.W. Wolfe. 1981. Labeled nitrogen uptake by drip-irrigated tomatoes. Agronomy Journal 73:265-270.

25. Miller, R.J., J.W. Biggar, G.L. Hoffman, and D.E. Rolston. October 1981. Water and salt movement in soils under drip irrigation. Division of Agricultural Sciences, University of California Bulletin 21259. pp. 3-6.

26. Rolston, D.E., A.N. Sharpley, D.W. Toy and F.E. Broadbent. 1982. Field measurement of denitrification: III. Rates during irrigation cycles. Soil Science Society of America Journal 46(2):289-296.

27. Rolston, D.E., R.D. Glauz, and B.D. Brown. 1982. Comparisons of simulated with measured transport and transformation of methyl bromide gas in soils. Pesticide Science 13:653-664.

28. Liss, H.J. and D.E. Rolston. 1983. Spatial and temporal variability of water soluble carbon for a cropped field. Agrochemical-Biota Interactions in Soil and Water Using Nuclear Techniques. International Atomic Energy Agency, Vienna. IAEA-TEC DOC-283. pp. 75-93.

29. Ryden, J.C. and D.E. Rolston. 1983. The measurement of denitrification. pp. 91-132. In: J.R. Freney and J.R. Simpson (eds.). Gaseous Loss of Nitrogen From Plant-Soil Systems, Martinus Nijoff/Dr. W. Junk Publishers. The Hague, The Netherlands.

30. Cervelli, S. and D.E. Rolston. October-December 1983. Influence of atrazine on denitrification in soil columns. Journal of Environmental Quality 12(4):482-486.

31. Rolston, D.E., P.S.C. Rao, J.M. Davidson, and R.E. Jessup. April 1984. Simulation of denitrification losses of nitrate fertilizer applied to uncropped, cropped, and manure-amended field plots. Soil Science 137(4):270-279.

32. Taghavi, S.A., M.A. Mariño and D.E. Rolston. 1984. Infiltration from trickle irrigation source. Journal of Irrigation and Drainage Engineering 110(4):331-341.

33. Biggar, J.W., D.E. Rolston, and D.R. Nielsen. 1984. Transport of salts by water. California Agriculture 38(10):10-11.

34. Rolston, D.E., J.W. Biggar, and D.R. Nielsen. 1984. Effect of salt on soils. California Agriculture 38(10):11-13.

35. Folorunso, O.A. and D.E. Rolston. 1984. Spatial variability of field-measured denitrification gas fluxes. Soil Science Society of America Journal 48(6):1214-1219.

36. Volker, R.E., M.A. Mariño, Members, ASCE, and D.E. Rolston. 1985. Transition zone width in ground water on ocean atolls. Journal of Hydraulic Engineering 111(4):659-676.

37. Morkoc, F., J.W. Biggar, D.R. Nielsen, and D.E. Rolston. August 1985. Analysis of soil water content and temperature using state-space approach. Soil Science Society of America Journal 49(4):798-803.

38. Taghavi, S.A., M.A. Mariño and D.E. Rolston. 1985. Infiltration from a trickle source in a heterogeneous soil medium. Journal of Hydrology 78:107-121.

39. Kachanoski, R.G., D.E. Rolston, and E. DeJong. 1985. Spatial and spectral relationships of soil properties and microtopography: I. density and thickness of A horizon. Soil Science Society of America Journal 49:804-811.

40. Kachanoski, R.G., E. DeJong and D.E. Rolston. 1985. Spatial and spectral relationships of soil properties and microtopography: II. density and thickness of B horizon. Soil Science Society of America Journal 49:812-816.

41. Angelakis, A.N. and D.E. Rolston. 1985. Transient movement and transformation of carbon species in soil during wastewater application. Water Resources Research 21:1141-1148.

42. Kachanoski, R.G., D.E. Rolston and E. De Jong. 1985. Spatial variability of a cultivated soil as affected by past and present microtopography. Soil Science Society of America Journal 49:1082-1087.

43. Folorunso, O.A. and D.E. Rolston. 1985. Spatial and spectral relationships between field-measured denitrification gas fluxes and soil properties. Soil Science Society of America Journal 49:1087-1093.

44. Sharples, R.A., D.E. Rolston, J.W. Biggar, and H.I. Nightingale. 1985. Evapotranspiration and soil water balances of young trickle-irrigated almond trees. Proceedings of the Third International Drip/Trickle Irrigation Congress. November 18-21. pp. 792-797.

45. Rolston, D.E. 1986. Limitations of the acetylene blockage technique for field measurement of denitrification. Field Measurement of Dinitrogen Fixation and Denitrification, SSSA Special Publication No. 18. pp. 93-101.

46. Rolston, D.E., R.J. Miller and H. Schulbach. 1986. Edited by F.S. Nakyama and D.A. Buck, Elsevier. Management principles. Trickle Irrigation for Crop Production. Developments in Agricultural Engineering 9. p. 317-344, Chapter 4.

47. Rolston, D.E. 1986. Gas diffusivity. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods - Agronomy Monograph no. 9 (2nd Edition). American Society of Agronomy- Soil Science Society of America. Madison, WI. pp. 1089-1102.

48. Rolston, D.E. 1986. Gas flux. In: Klute, A. (ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods - Agronomy Monograph no. 9 (2nd Edition). American Society of Agronomy, Soil Science Society of America. pp. 1103-1119.

49. Grundmann, G.L. and D.E. Rolston. 1987. A water function approximation to degree of anaerobiosis associated with denitrification. Soil Science. 144:437-441.

50. Angelakis, A.N., T.N. Kadir and D.E. Rolston. 1987. Solutions for transport of two sorbed solutes with differing dispersion coefficients in soil. Soil Science Society of America Journal. 51:1428-1434.

51. van Wesenbeeck, I.J., R.G. Kachanoski and D.E. Rolston. 1988. Temporal persistence of spatial patterns of soil water content in the tilled layer under a corn crop. Soil Science Society of America Journal. 52:934-941.

52. Grundmann, G.L., D.E. Rolston and R.G. Kachanoski. 1988. Field soil properties influencing the variability of denitrification gas fluxes. Soil Science Society of America Journal. 52:1351-1355.

53. Biggar, J.W., W.R. Tillotson, D.E. Rolston and D.R. Nielsen. 1988. Selenium in crops grown on soil with established selenium distributions. pp. 47-50 in Selenium Contents in Animal and Human Food Crops Grown in California. Division of Agricultural Sciences Special Publication #3330.

54. Broadbent, F.E., T. Nakashima, and D.E. Rolston. 1988. Effects of salinity and moisture gradients on nitrogen uptake by sorgum and wheat. Soil Science. 146,4:232-240.

55. Angelakis, A.N., T.N. Kadir, D.E. Rolston and P.D. Brooks. 1989. An analytical solution for diffusion of soil gas produced from a moving solute. Soil Science. 147:(4):270-277.

56. Rolston D.E. and H.J. Liss. 1989. Spatial and temporal variability of water-soluble organic carbon in a cropped field. Hilgardia. 57:3:1-19.

57. Moldrup, P., D.E. Rolston, and J. AA. Hansen. 1989. Rapid and numerically stable simulation of one-dimensional, transient water flow in unsaturated, layered soils. Soil Science. 148:(3):219-226.

58. Rolston, D.E. 1989. Gaseous losses. In: Nitrogen in Organic Wastes Applied to Soils. J.Aa. Hansen and K. Henriksen (eds.), Academic Press, New York. 365-369.

59. Glauz, R.D. and D.E. Rolston. 1989. Optimal design of two-chamber, gas diffusion cells. Soil Science Society of America Journal 53:(6):1619-1623.

60. Van Genuchten, M.Th., D.E. Rolston and P.F. Germann. Eds. 1990. Transport of water and solutes in macropores. Geoderma, special issue Vol 46, Elsevier, Amsterdam. 297 pages.

61. Rolston, D.E. 1990. Modeling of denitrification: approaches, successes and problems. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 60:397-402.

62. Yamaguchi, T., P. Moldrup, S. Teranishi, and D.E. Rolston. 1990. Denitrification in porous media during rapid, continuous leaching of synthetic wastewater at saturated water flow. J. Environ. Qual. 19:676-683.

63. Rolston, D.E., S. Amali, G.R. Jayaweera, P.S.C. Rao, R.E. Jessup, D.S. Mikkelsen and K.R. Reddy. 1991. Simulation of nitrogen transport processes in flooded rice soils. Transactions of the 14 International Congress of Soil Science. 4:314-319.

64. Rolston, D.E., M.N.A. Bedaiwy, and D.T. Louie. 1991. Micropenetrometer for in situ measurement of soil surface strength. Soil Science Society of America Journal 55:481-485.

65. Nightingale, H.I., G.J. Hoffman, D.E. Rolston and J.W. Biggar. 1991. Trickle irrigation rates and soil salinity distribution in an almond (*Prunus amygdalus*) orchard. Agricultural Water Management 19:271-283.

66. Rolston, D.E., J.W. Biggar, and H.I. Nightingale. 1991. Temporal persistence of spatial soil-water patterns under trickle irrigation. Irrigation Science 12:181-186.

67. Rolston, D.E., R.D. Glauz, G.L. Grundmann, and D.T. Louie. 1991. Evaluation of an in situ method for measurement of gas diffusivity in surface soils. Soil Science Society of America Journal 55:1536-1542.

68. Lucas, A.D., P. Schneider, RO. Harrison, J.N. Seiber, B.D. Hammock, J.W. Biggar and D.E. Rolston. 1991. Determination of atrazine and simazine in water and soil using polyclonal and monoclonal antibodies in enzyme-linked immunosorbent assays. Food & Ag. Immunology 3:155-167.

69. Moldrup, P. D.E. Rolston, J.AA. Hansen, and T. Yamaguchi. 1992. A simple, mechanistic model for soil resistance to plant water uptake. Soil Science 153, No. 2 87-93.

70. Moldrup, P., T. Yamaguchi, J.A.A. Hansen, and D.E. Rolston. 1992. An accurate and nummerically stable model for one-dimensional solute transport in soils. Soil Science 153, No. 4 261-273.

71. Govindaraju, R.S., D. Or, M.L. Kavvas, D.E. Rolston, and J. Biggar. 1992. Error analyses of simplified unsaturated flow models under large uncertainty in hydraulic properties. Water Resources Research 28:(11):2913-2924.

72. Folorunso, O.A., D.E. Rolston, T. Prichard, and D.T. Louie. 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technology 5:189-197.

73. Folorunso, O.A., D.E. Rolston, T. Prichard, and D.T. Louie. 1992. Cover crops lower soil surface strength, may improve soil permeability. California Agriculture 46:(6):26-27.

74. Kavvas, M.L., R.S. Goviandaraju, D.E. Rolston, D. Or, and J. Biggar. 1992. On the stochastic pollution transport equations. In: M. Quintard and M. Todorović (eds.), Heat & Mass Transfer in Porous Media, Elsevier, New York. pp. 136-142.

75. McCoy, Benjamin J. and D.E. Rolston. 1992. Convective transport of gases in moist porous media: effect of absorption, adsorption, and diffusion in soil aggregates. Environ. Sci. Technol., 26:(12):2468-2476.

76. Rolston, D.E. (Member of Writing Committee). 1992. G. Sposito and R.J. Reginato (eds). Opportunities in Basic Soil Science Research. Soil Science Society of America, Madison, Wisconsin. 109 pp.

77. Rolston, D.E. (chair of editorial committee), L.A. Harper, A.R. Mosier, J.M. Duxbury (eds.). 1993. Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. ASA Special Publication #55. American Society of Agronomy, Madison, WI. 206 pp.

78. Yamaguchi, T., P. Moldrup, D.E. Rolston, and J. AA. Hansen. 1992. A simple, inverse model for estimating nitrogen reaction rates from soil column leaching experiments at steady water flow. Soil Science 154:(6):490-496.

79. Moldrup, P., J. AA. Hansen, D.E. Rolston, and T. Yamaguchi. 1993. Improved simulation of unsaturated soil hydraulic conductivity by the moving mean slope approach. Soil Science 155:(1):8-14.

80. Angelakis, A.N., T.N. Kadir, and D.E. Rolston. 1993. Analytical solutions for equations describing coupled transport of two solutes and a gaseous product in soil. Water Resources Research, 29:4:945-956.

81. McCoy, B.J. and D.E. Rolston. 1993. Effects of combined adsorption and absorption in migration of soil contaminants. Fundamentals of

Adsorption 1993. Proc. IVth Int. Conf. on Fundamentals of Adsorption, Kyoto, Japan, May 17-22, p. 429-436.

82. Angelakis, A.N., D.E. Rolston, T.N. Kadir, and V.H. Scott. 1993. Soil-water distribution under trickle source. J. of Irrigation and Drainage Engineering. 119:484-500.

83. Amali, S. and D. E. Rolston. 1993. Theoretical investigation of multicomponent volatile organic vapor diffusion: steady-state fluxes. J. Environ. Qual. 22:825-831.

84. Amali, S., L.W. Petersen, and D.F. Rolston. 1994. Modeling multicomponent volatile organic and water vapor adsorption on soils. J. of Hazardous Materials 36:89-108.

85. Bedaiwy, M.N. and D.E. Rolston. 1993. Soil surface densification under simulated high intensity rainfall. Soil Technology 6:365-376.

86. Moldrup, P., T. Yamaguchi, D.E. Rolston, and J. Aa. Hansen. 1994. Estimation of the soil-water sorptivity from infiltration in vertical soil columns. Soil Science. 157:(1)12-18.

87. Folorunso, O.A., C.E. Puente, D.E. Rolston, and J.E. Pinzon. 1994. Statistical and fractal evaluation of the spatial characteristics of soil surface strength. Soil Sci. Am. J. 58:284-294.

88. Moldrup, P., T.G. Poulsen, D.E. Rolston, T. Yamaguchi, and J. AA. Hansen. 1994. Integrated flux model for unsteady transport of trace organic chemicals in soils. Soil Sci. 157:(3):137-152.

89. Moldrup, P., T. Yamaguchi, D.E. Rolston, K. Vestergaard, and J. AA. Hansen. 1994. Removing numerically induced dispersion from finite difference models for solute and water transport in unsaturated soils. Soil Sci. 157:(3):153-161.

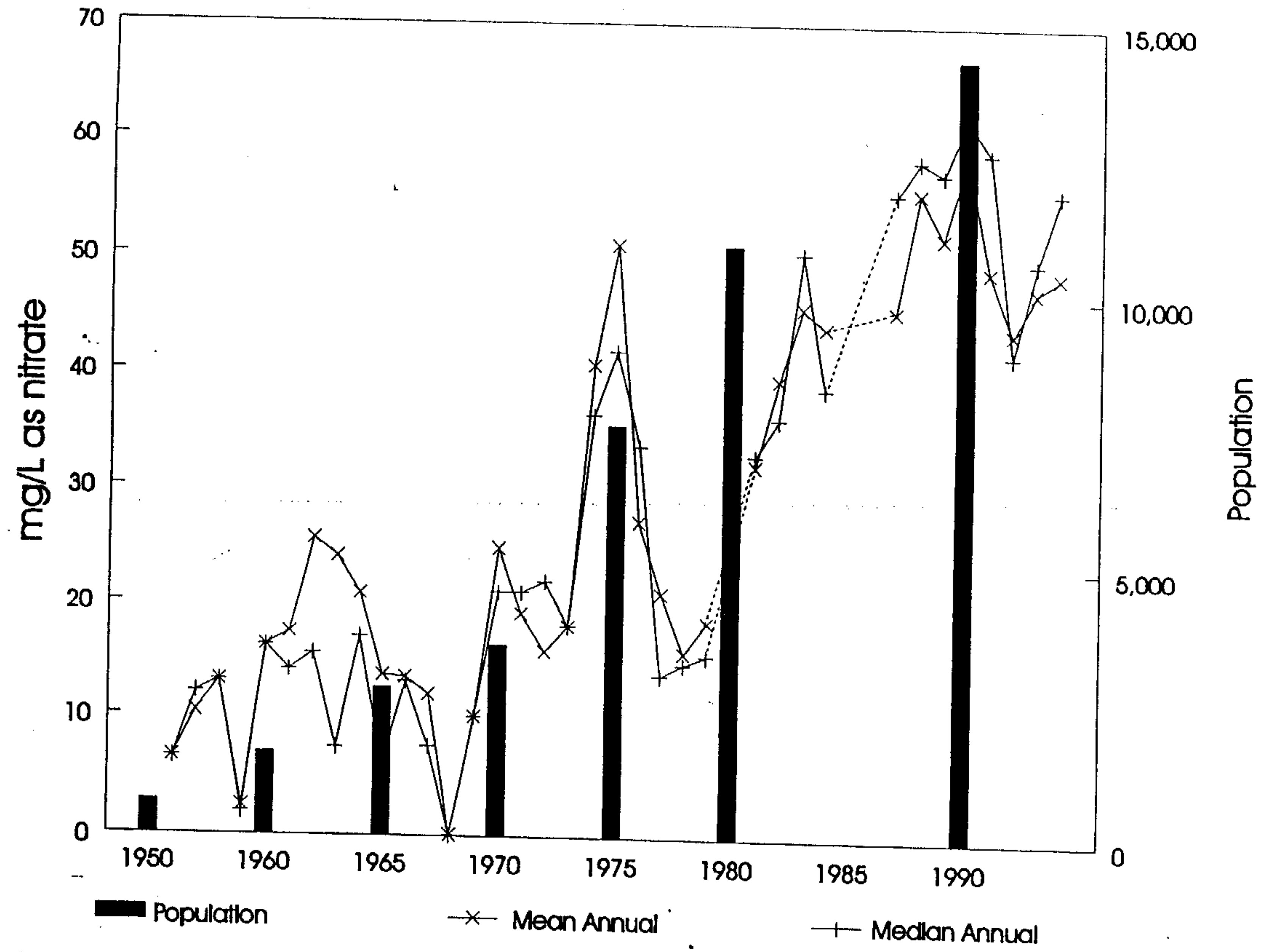
90. Ben-Asher, J., G.E. Cardon, D. Peters, D.E. Rolston, J.W. Biggar, C.J. Phene, and J.E. Ephrath. 1994. Determining root activity distribution by measuring surface carbon dioxide fluxes. Soil Sci. Soc. Am. J. 58:926-930.

91. Ben-Asher, J., G.E. Cardon, D. Peters, D.E. Rolston, C.J. Phene, J.W. Biggar, and R.B. Hutmacher. 1994. Determining almond root zone from surface carbon dioxide fluxes. Soil Sci. Soc. Am. J. 58:930-934.

92. Marion, J.M., D. Or, D.E. Rolston, M.L. Kavvas, and J.W. Biggar. 1994. Evaluation of methods for determining soil-water retentivity and unsaturated hydraulic conductivity. Soil Sci. 158:(1):1-13.

93. Yamaguchi, T., P. Moldrup, D.E. Rolston, and L. W. Petersen. 1994. A semi-analytical solution for one-dimensional solute transport in soils. Soil Sci. 158:14-21.

94. Petersen, L.W., D.E. Rolston, P. Moldrup, and T. Yamaguchi. 1994. Volatile organic vapor diffusion and adsorption in soils. J. Env. Qual. 23:799-805.



DRAFT

Los Osos Wastewater Study	Figure 3-1
Average Annual Nitrate Concentrations and Population	
M&E Metcalf & Eddy	Date: October 1994

ATTACHMENT 3