A COMPARATIVE LABORATORY STUDY OF SEWAGE TREATMENT BY A CAPILLARY SIPHON TRENCH SYSTEM VERSUS A CONVENTIONAL LEACHING TRENCH SYSTEM

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ABSTRACT

Laboratory tests were conducted to investigate the performance of the "Niimi Process" or capillary siphon trench, a soil based wastewater disposal system common in Japan. The system is similar to conventional septic tank leaching field trenches except that the trenches are filled with capillary sand instead of gravel and the lower quarter of the trench is lined with an impermeable membrane. The capillary sand and impermeable membrane are used to induce the unsaturated flow of wastewater through the upper soil profile, or zone of aeration, where maximum biological activity occurs. According to Japanese scientists, this results in improved organics and nutrient removal.

The Niimi Process was evaluated by constructing a laboratory scale Niimi Process trench and a conventional soil absorption trench. Synthetic wastewater characteristic of domestic sewage was then applied to the two trenches in two 14-week experiments. No statistically significant differences were found between the operation of the two systems for the soil and synthetic wastes except for NO_3-N and Total-N removal during the second experiment where the Niimi trench was slightly more effective. Both reactors removed 99 percent of the applied COD, 95-99 percent of the applied phosphorus and 18-31 percent of the total nitrogen. The hypothesis that the Niimi trench was superior to the conventional trench was not demonstrated.

Key words: Water quality, wastewater treatment, Nutrient removal, Onsite wastewater treatment, soil absorption, capillary siphon trench, Niimi process.

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INTRODUCTION

Wastewater treatment using the natural purification capacity of soil has been practiced for thousands of years and is the primary waste disposal technique in rural areas of the world. Soil based treatment systems are attracting increased attention in urban and other developed areas because of: 1) the necessity for low cost waste treatment systems in low density areas where centralized conventional facilities are cost prohibitive; 2) the need for mechanically simple systems appropriate for less developed areas of the world; and 3) the implementation of Public Law 92-500 with its mandate to improve the Nation's surface water quality and move towards zero discharge.

Published research on the many aspects of onsite treatment and land disposal are extensive as summarized by Overcash and Pal (1974, Boyle and Otis (1983), and Iskander (1981). Conventional soil treatment systems usually involve the application of wastewater to the soil surface or to subsurface gravel filled trenches. Typically, the wastewater is treated as it percolates downward through the soil profile. An alternative treatment system is the capillary siphon trench (CST) or "Niimi Process" which relies upon biological processes and capillary phenomena for wastewater treatment. Currently, there are over 30,000 Niimi systems in operation in Japan and other units are now being installed in Hawaii, Malaysia, and the Commonwealth of the Northern Marianas.

The Niimi system has attracted interest in Guam because of concern over increasing levels of nitrate in the groundwater of Northern Guam, the island's primary potable water source. It is suspected that inadequate domestic leaching fields are a primary source of nitrate in the northern lens. Japanese scientists have reported that the Niimi system is superior to conventional leaching systems with respect to organics, pathogen, phosphorus and nitrogen removal. If the system is more effective in removing nitrogen, then it may be an economic solution to Guam's groundwater nitrate problem.

The results presented herein are part of the findings of a joint research project investigating the Niimi Process between the University of Guam, Virginia Polytechnic Institute and State University, Meiji University (Japan), and the University of Malaysia. Primary goals of the joint research effort were to evaluate the system for soils other than those found in Japan, which are almost exclusively clays of volcanic origin, and to compare its performance with conventional gravel trenches.

OBJECTIVES

The design and operation of domestic onsite wastewater disposal systems is generally based upon custom and empirical methods derived from the performance of existing systems. Typical design standards are based upon soil percolation and hydraulic loading rates. Existing design standards in Guam do not appear to be adequate with respect to nitrogen removal. This is primarily a result of the soils of Northern Guam which are often too shallow for efficient soil absorption field operations. An onsite domestic wastewater disposal system, the Niimi Process, has been proposed for use in Guam to overcome the nitrate pollution problem but the system has not been tested outside of Japan and design standards are not available for other soils and climates. The objectives of this study are therefore to investigate the Niimi system's performance for Guam's soils and climatic conditions and to determine if it is appropriate for use in Guam. This will enable planners and health workers to evaluate the merits of the system in relation to conventional systems.

The specific objectives of this study are:

1. Describe the technical concept of the Niimi Process.

2. Compare the performance of the Niimi system with that of a conventional system on a Guam soil.

3. Evaluate the suitability of the Niimi Process for onsite domestic wastewater treatment in Guam.

TECHNICAL CONCEPTS

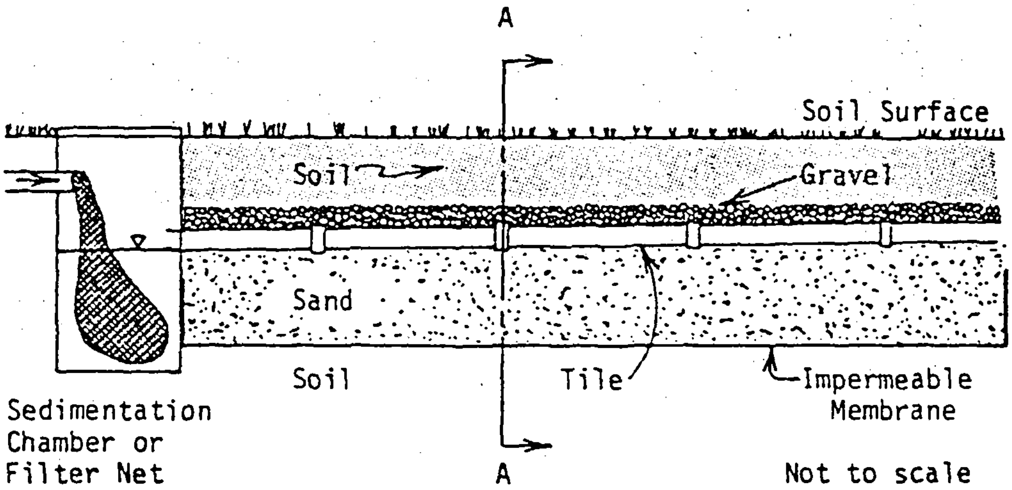
With conventional soil based land application systems, wastewater applied to the soil moves downward and treatment is accomplished by a combination of physical and biological processes. In heavily loaded or continuous application systems, the soil pores are often saturated with wastewater which causes oxygen depletion in anaerobic conditions. Under anaerobic conditions, the soil's wastewater treatment mechanism is primarily one of filtration and the soil's pores are susceptible to biological and physical clogging. Anaerobic conditions intensify clogging because anaerobic soil organisms are not as efficient as aerobic organisms in removing accumulated organic matter. Clogging therefore intensifies under anaerobic conditions, infiltration and percolation rates decrease, surface runoff occurs and system failure may result.

Soil based wastewater treatment is most efficient if unsaturate flow is maintained in the zone of aeration. This allows a continuous supply of oxygen to soil organisms and plant roots. Under these circumstances, biological activity is high and the optimum assimilative capacity of the soil for wastewater treatment is achieved.

The Niimi Process was developed by Tadashi Niimi in Japan during the 1950's. Niimi observed that the zone aeration (upper 50 cm or so of the soil profile) was the principal habitat of soil organisms and that decomposition of organic matter was most active within this region. He reasoned that wastewater applied below the zone of aeration would intensify clogging since this region was biologically less active than the upper aerobic zone. Niimi therefore attempted to develop a soil based wastewater treatment system which would introduce wastewater into the zone of aeration an insure aerobic conditions by encouraging unsaturated flow through the upper soil profile.

The CST system is similar to conventional septic tank/tile absorption field systems used in the United States. The system employs a conventional settling tank or filter for solids removal followed by a series of sand filled trenches with impermeable linings. It is the sand filled trench with its impermeable lining that is the unique part of the CST. Figure 1 is a diagram of a typical CST system showing a chamber with a fine mesh bag for removing suspended solids and a soil absorption trench. In Japan, solids from the mesh bags are removed weekly and disposed of by the land owners or a private service. If filter bags are not used then the trench is preceded by a conventional septic tank, or more commonly in Japan, a small extended aeration unit followed by a settling chamber. Capillary siphon trench design value was derived from thirty years of field experience with the system in Japan but may not be appropriate for other soils and climatic conditions.

As shown in Figure 1, a Niimi trench is similar to a conventional tile absorption trench except that the lower 10 cm of the trench is lined with an impermeable plastic membrane to prevent the immediate downward percolation of tile effluent. In a conventional soil treatment system, the trench is filled with gravel but in the CST a 20 cm layer of fine sand, referred to as capillary sand, is added first. The tile is then place and



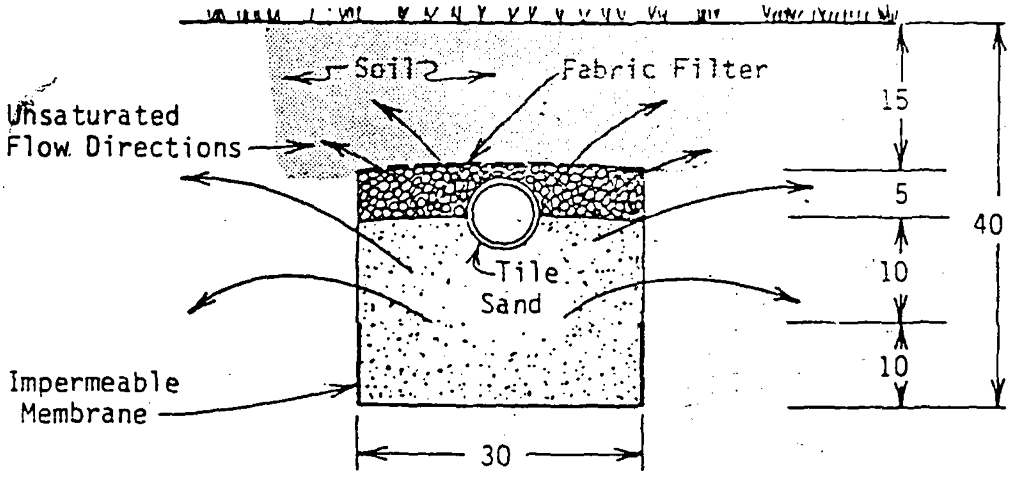


Figure 1. Niimi System

covered with gravel and a conventional filter fabric to prevent the soil backfill from entering the gravel layer.

The purpose of the impermeable membrane and capillary sand layer in the CST is to increase the residence time of wastewater within the zone of aeration by reducing the immediate downward percolation to tile effluent. In theory, the sand mass saturates and temporarily stores the wastewater, thus reducing the onset of percolation. Wastewater in excess of the sand mass storage quantity spills over the sides of the impermeable membrane and percolates downward through the soil as it would in a conventional trench. After tile inflow stops (typical of the intermittent flow characteristics of small onsite systems), the accumulated wastewater in the sand begins to move upward and outward into the soil profile by capillary action. Because this flow is due to capillary forces, flow into the surrounding soil is primarily unsaturated and the soil is more likely to remain aerobic. Since the wastewater is induced to flow through the aerobic region of maximum biological activity, dissolved organics in the wastewater should be removed to a greater degree than those in conventional gravel trenches where flow is predominantly saturated and downward through anaerobic soil layers. Suspended organic and inorganic particulate matter in the wastewater are not transported by capillary flow and will thus remain in the gravel and sand layers.

As in conventional trenches, larger soil organisms such as worms and insects are crucial to the successful operation of the CST. The larger organisms are important because they remove biological growth and organic solids from the gravel and sand layer and maintain their porosity. Since larger soil organisms are aerobic, a well aerated system like the CST should benefit from higher soil macro invertebrate populations and improved wastewater treatment can be expected.

Some Japanese scientists have postulated that the Niimi system will be superior to conventional trenches in controlling nitrogen pollution because the sand layer will alternate between and aerobic and an anaerobic state which will encourage denitrification and because increased biological activity will promote nitrogen immobilization. An investigation of this hypothesis is a primary goal of the present study.

With respect to fecal bacteria, the capillary siphon trench should be superior in removing these organisms if unsaturated flow predominates because bacteria are not transported well by unsaturated flow. Also, increased biological activity and competition from aerobic soil microrganisms will contribute to increased mortality of fecal bacteria.

It should be noted that the theoretical operations of the CST system is similar in many respects to that of a mound system. Both systems seek to increase the distance that the effluent must travel through aerated soil before it reaches a water table or other region of reduced biological activity.

EXPERIMENTAL APPARATUS AND METHODS

Experimental Apparatus

Laboratory scale capillary siphon and conventional soil absorption trenches were constructed at the University of Guam, the University of Malaysia and Meiji University to evaluate the relative performance of the Niimi system and conventional gravel filled trenches. Only the Guam reactors will be discussed here as the results of the Malaysian and Japanese reactor studies will be presented elsewhere.

The experimental capillary siphon trench apparatus or reactor is presented in Figure 2. As shown in figure, the reactor had a volume of approximately 0.5 m^3. The rector was constructed using 2 cm marine plywood and sealed with fiberglass. The reactor was filled with a Guam limestone clay which was compacted in layers to approximate the soil's original bulk density. Table 1 is a summary of the soil's properties prior to wastewater application. Soil analysis was provided by the Soil Testing Lab at the University of Guam using standard soil testing procedures.

Table 1. Soil Properties

Parameter	Value
Sand, %	25
Silt, %	24
Clay, %	51
Texture	clay
Organic Matter, %	3.7
pH	7.85
Phosphorus, ppm	4.5
Potassium, ppm	40.0
Calcium, ppm	9000
Magnesium, ppm	420
Sodium, ppm	68.6

At the depths and locations indicated in Figure 2, cords of capillary fiberglass were placed for sample collection. Previous work at Meiji University had shown that the capillary cords would draw sufficient water from the soil for water quality analysis. After the soil and capillary cords have places in the reactor and compacted, a trench with the dimensions indicated in Figure 2 was excavated. The lower 10 cm of the trench was then lined with an impermeable polyethylene plastic membrane to seal the lower portion of the trench. A 20 cm layer of compacted fine sand was then added to the trench. The sand, which was made from crushed limestone, was fine and well graded. A conventional plastic drain pipe with an inlet was places on the sand layer and then covered with a 5 cm layer of 1 to 2 cm diameter gravel (crushed limestone). The gravel layer was then covered with a fabric filter to prevent the 15 cm of soil which was used for trench backfill from entering and clogging the gravel layer.

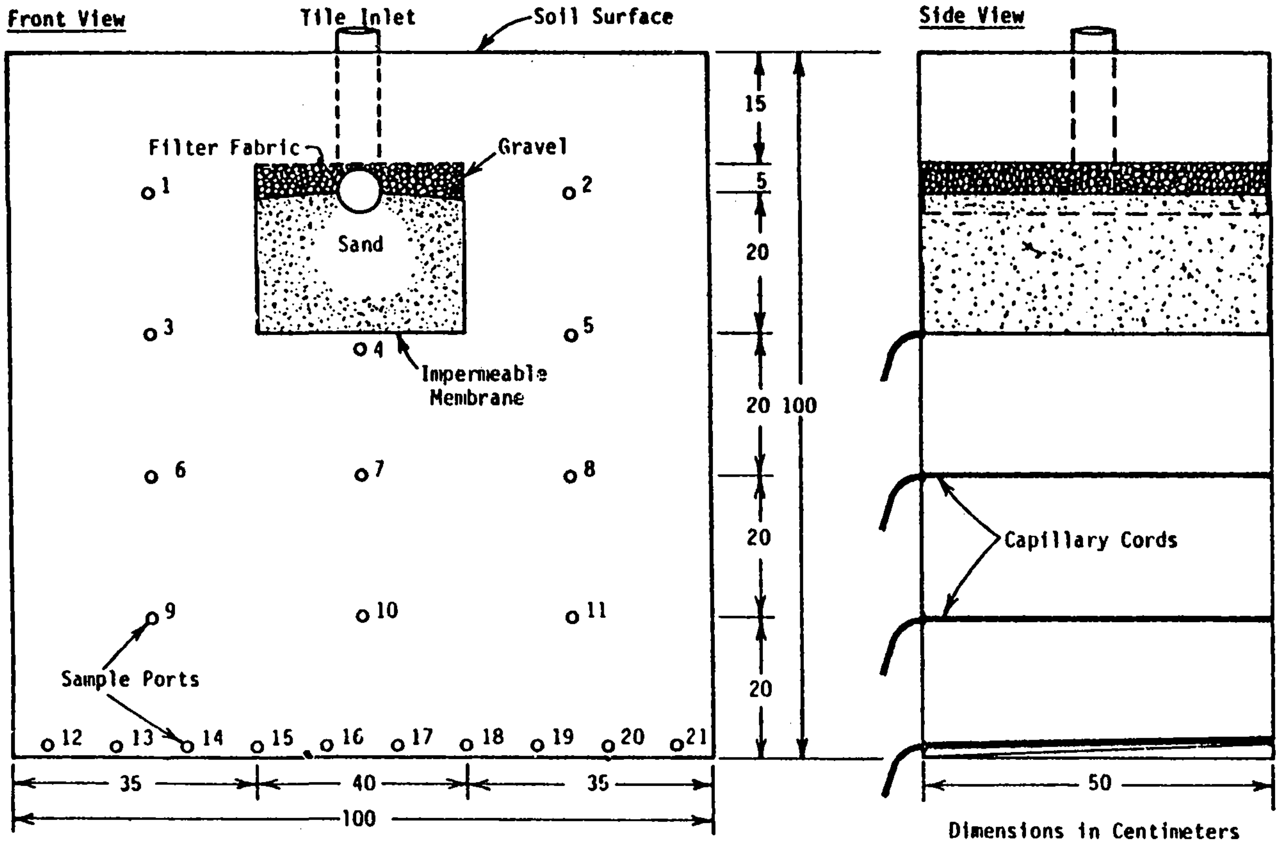


Figure 2. Experimental Capillary Siphon Trench

A second reactor was constructed to simulate the performance of a conventional gravel filled soil absorption trench. It was identical to the CST reactor except that there was no impermeable membrane, the sand was replace with gravel and the entire gravel mass was surrounded by the fabric filter.

Experimental Methods

After the reactors were constructed, 10 l/day of reverse osmosis water was applied to the reactors for a month to help stablize the soil structure. Raw domestic sewage from the Dededo Pump Station was then added to the reactors (10 l/day) for one week to seed the soil and induce increased biological activity. The reactors were allowed to rest for one week and synthetic sewage application was then initiated.

Reactor performance was evaluated by applying synthetic sewage of two different strengths to the reactors from August 1983 to March 1984. During the first experiment, Run I, a synthetic waste composed of 0.035 percent dark molasses and 0.005 percent urea, which approximated a weak domestic sewage, was used. The synthetic waste used in the second experiment, Run II, consisted of 0.035 percent dark molasses, 0.01 percent urea and 0.025 percent powdered nonfat dry milk. The synthetic waste of Run II was approximately twice as strong as the waste of Run I with respect to COD and Total-N. The synthetic sewage was prepared daily and stored in a refrigerator at 2°C prior to use.

Ten liters of synthetic sewage were introduced to the reactors through the tile inlet each day. Five liters were applied at 0800 and 1700 hours except on weekends when the reactors were allowed to rest. As shown in Figure 2, the reactors had 21 sample ports. The effluent from each port was collected twice daily prior to influent loading, and its volume was recorded. Samples for water quality analysis were collected and analyzed once per week since the reactor effluents were expected to be reasonably stable. The samples were analyzed according to the procedures given in Standard Methods (1981) for pH, conductivity, total residue, COD, BOD_5, NH_4-N, NO_2-N, NO_3-N, TKN, PO_4-P and Total-P.

Statistical Procedures

The performance of the reactors was compared using statistical routines from the Statistical Package for the Social Sciences (1975). The T-Test routine for paired data was used to determine if there were any statistical difference between the operation of the reactors with respect to COD, nitrogen and phosphorus removal. All tests were performed at the 95 percent confidence level.

RESULTS AND DISCUSSION

Synthetic sewage was applied to the reactors for two 14 week periods beginning on August 7, 1983, and November 28, 1983, respectively. Table 2 is a summary of the chemical characteristics of the synthetic wastes which are applied to the reactors and the effluent from the reactors. As shown in Table 2, the Niimi reactor was slightly more effective in removing NH_4-N, NO_2-N, TKN-N and Total-P while the conventional trench had slightly lower effluent COD values. Total-N and NO_3-N removal was greater in the Niimi reactor during Run II but the conventional trench had the best removal during Run I. None of these differences were statistically significant at the 95 percent confidence level except for NO_3-N and Total-N removal during Run II. The reactors removed 99 percent of the applied COD, 95-99 percent of the applied phosphorus and 18-31 percent of the applied nitrogen.

A comparison of the reactor's performance for flow, COD and total nitrogen is presented in Figures 3 and 4. Part C of the figures is a comparison of the mean weekly flows from the two reactors. The observed flows are similar but demonstrate some of the differences predicted by Niimi Process theory. Although the differences are not large, the Niimi reactor appears to have slightly lower flows from the ports under the trench and higher flows from the outside ports. This supports the hypothesis that the Niimi trench induces increased lateral flow. Parts A and B of Figures 3 and 4 show the variations in Total-N and COD's under the Niimi trench (ports 15, 16 and 17) are higher than those under the conventional trench. This is the opposite of what was expected and the reasons for this behavior are unknown but will be investigated further in future research.

As indicated in Table 2 and Figures 3 and 4, the two trenches had nearly identical effects upon applied nitrogen. Ninety-six to 98 percent of the applied nitrogen was in the form of organic nitrogen while the effluent from both reactors was almost exclusively NO_3-N (99%). Both reactors were thus highly aerobic at the present loadings. Denitrification, volatilization and nitrogen immobilization were presumably responsible for the effluent nitrogen reductions.

The hypothesis that organics removal would be superior with the Niimi system was not demonstrated. The conventional system had lower effluent COD's during both experimental runs but this may have been due to the difference in flow from Port 4 of the reactors. The flow from Port 4 of the conventional trench average 2800 mℓ/week while that form the Niimi reactor averaged 850 mℓ/week.

The hypothesis that nitrogen removal would be better with the Niimi system was not demonstrated conclusively. Run I, which used synthetic sewage characteristic of medium strength domestic sewage, produced no statistically significant differences in effluent Total-N. The Niimi reactor had a statistically significant lower effluent Total-N during Run II, but the synthetic waste used was much stronger than domestic sewage on Guam and the results are not, therefore, appropriate for Guam conditions.

Table 2. Synthetic Waste and Reactors Effluent Characteristics.

PARAMETER	REACTOR INFLUENT (SYNTHETIC WASTE) MG/ℓ	MG/DAY	REACTOR EFFLUENT (PORTS 12-21) NIIMI TRENCH MG/ℓ	MG/DAY	%REMOVAL	CONVENTIONAL TRENCH MG/ℓ	MG/DAY	%REMOVAL	LEVEL OF SIGNIFICANCE
Run I									
Volume (1/day)	(10.0)	--	(0.1)	--	--	(7.7)	--	--	.003
COD	266.	2660	4.8	38.9	99	4.4	34.2	99	.501
NH3-N	0.224	2.24	0.006	0.053	98	0.007	0.054	98	.851
NO2-N	0.009	0.09	0.001	0.012	87	0.003	0.023	74	.066
NO3-N	1.04	10.4	26.6	215	--	26.1	201	--	.120
TKN-N	25.2	252	0.197	1.59	99	0.302	2.33	99	.081
Total-N	26.5	265	26.8	216	18	26.4	203	23	.129
Total-P	0.106	1.06	0.007	0.053	95	0.007	0.058	95	.310
Run II									
Volume (1/day)	(10.0)	--	(7.9)	--	--	(7.6)	--	--	.048
COD	557.	5570.	4.4	34.8	99	3.3	25.0	99.6	.083
NH3-N	0.167	1.67	0.007	0.054	97	0.008	0.064	96	.103
NO2-N	0.016	0.16	0.004	0.029	82	0.005	0.035	78	.356
NO3-N	1.09	10.9	48.3	380	--	53.6	406	--	.002*
TKN-N	54.2	542	0.125	.985	99.8	0.173	1.03	99.8	.571*
Total-N	55.5	555	48.4	381	31	53.8	497	27	.002*
Total-P	2.404	24.04	0.004	0.031	99.9	0.004	99.9	.891	

*Statistically significant difference at the 95 percent confidence level.

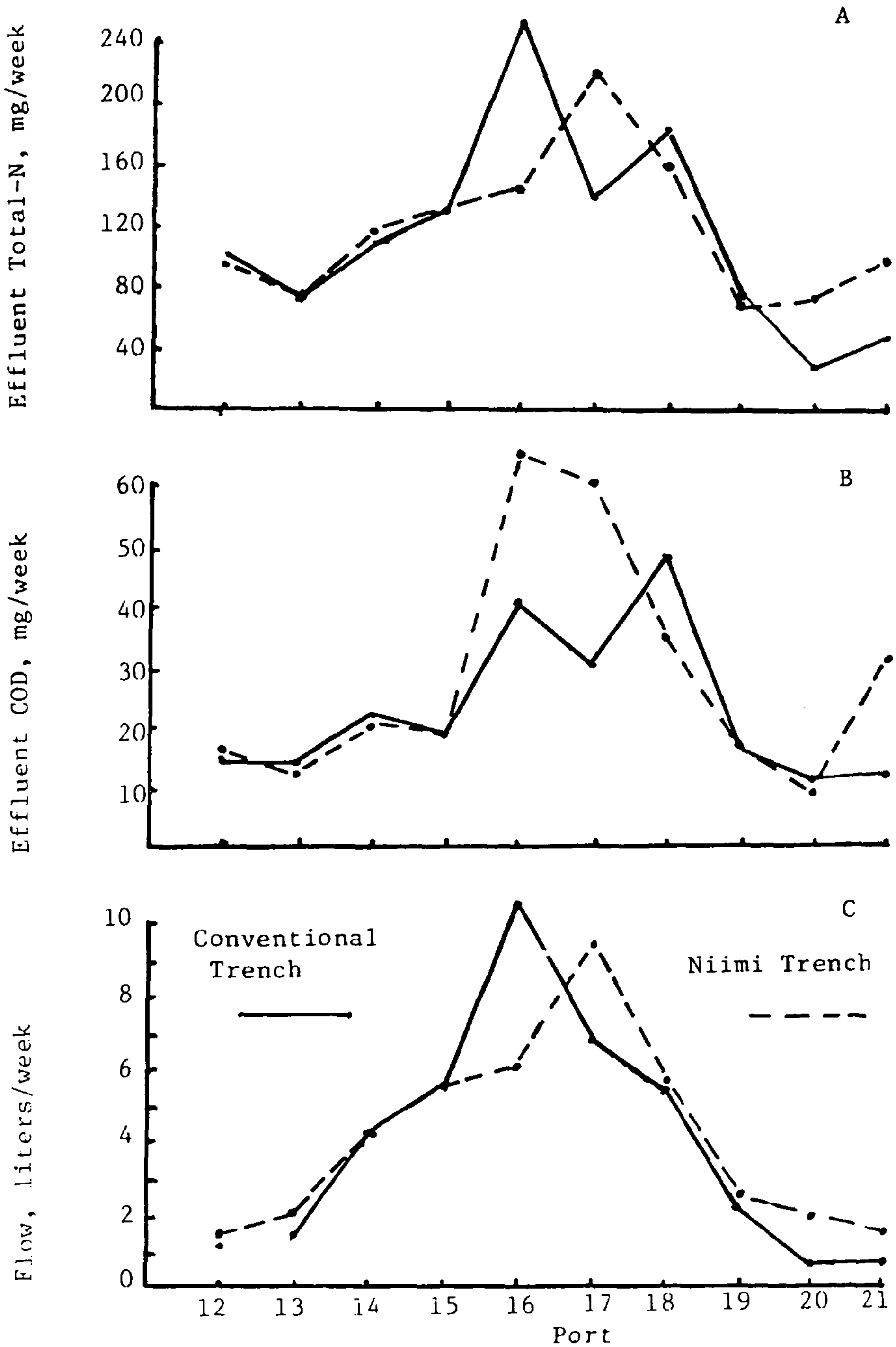


Figure 3. Reactor Performance, Run 1.

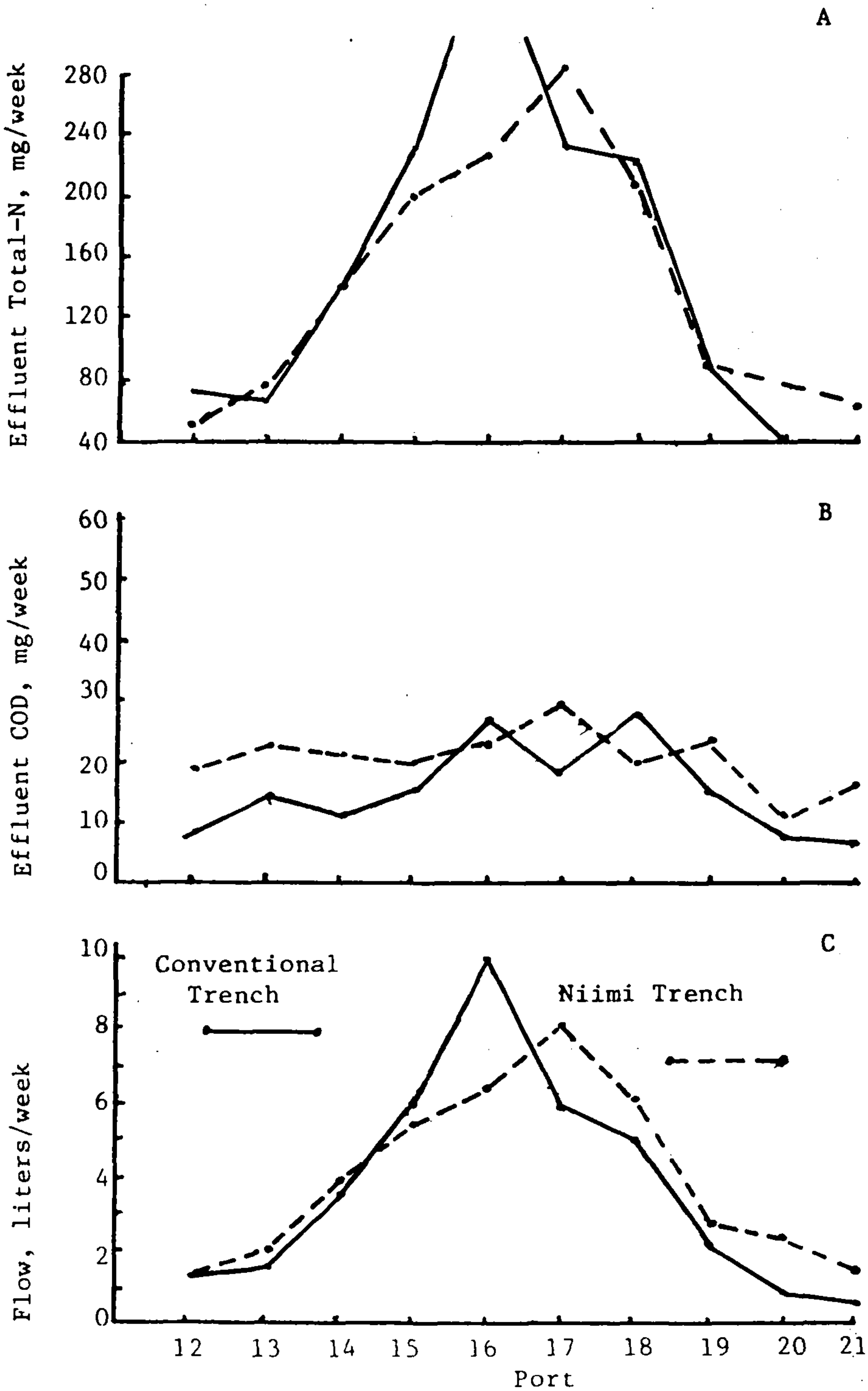


Figure 4. Reactor Performance, Run II

Japanese scientists at Meiji University have reported similar preliminary results suggesting that there is little, if any, difference between the performance of capillary siphon and conventional trenches at low influent loadings (less that 500 mg/ℓ COD). Their preliminary results indicate that the capillary siphon trench does not show significant improvement over the conventional trench until loadings exceed 1000 mg/ℓ COD.

Several problems were encountered during the study which may have had adverse impact on the results. One problem was that the chemical composition of the effluent did not stabilize as expected during the two 14 week experimental runs. Figure 5 shows the variability of the effluent COD values during Runs I and II. As shown in the figure, neither reactor reached and equilibrium state. This greatly increased effluent variance and may have masked some significant differences between the two reactors.

Flow determinations were complicated by the occurrence of a leak (approximately 4600 and 3725 mℓ/week during Runs I and II, respectively) in the conventional trench reactor near port 18. Attempts to seal the leak were unsuccessful. Analysis of the flow data indicated that the flow from ports 18 and 19 were unreasonably low so the leak was apportioned between these ports in subsequent mass flow calculations. Problems were also experienced with ports 1, 2, 3 and 5 to 11 of both reactors, as these ports rarely had effluent. Apparently, the capillary cords worked only under saturated conditions.

Analysis of nitrogen dynamics and removal rates in the reactors is questionable because the TKN test results were much lower than the expected theoretical values. Theoretical influent TKN to the reactors should have been at least 25 mg/ℓ but laboratory analysis gave only 6.3 mg/ℓ. It is suspected that the digestion temperature used in the TKN digestion procedure was too low and the digestion process was therefore incomplete. Based on sewage digestions run during experiment and after, the TKN results have been corrected using a factor taking into account this problem.

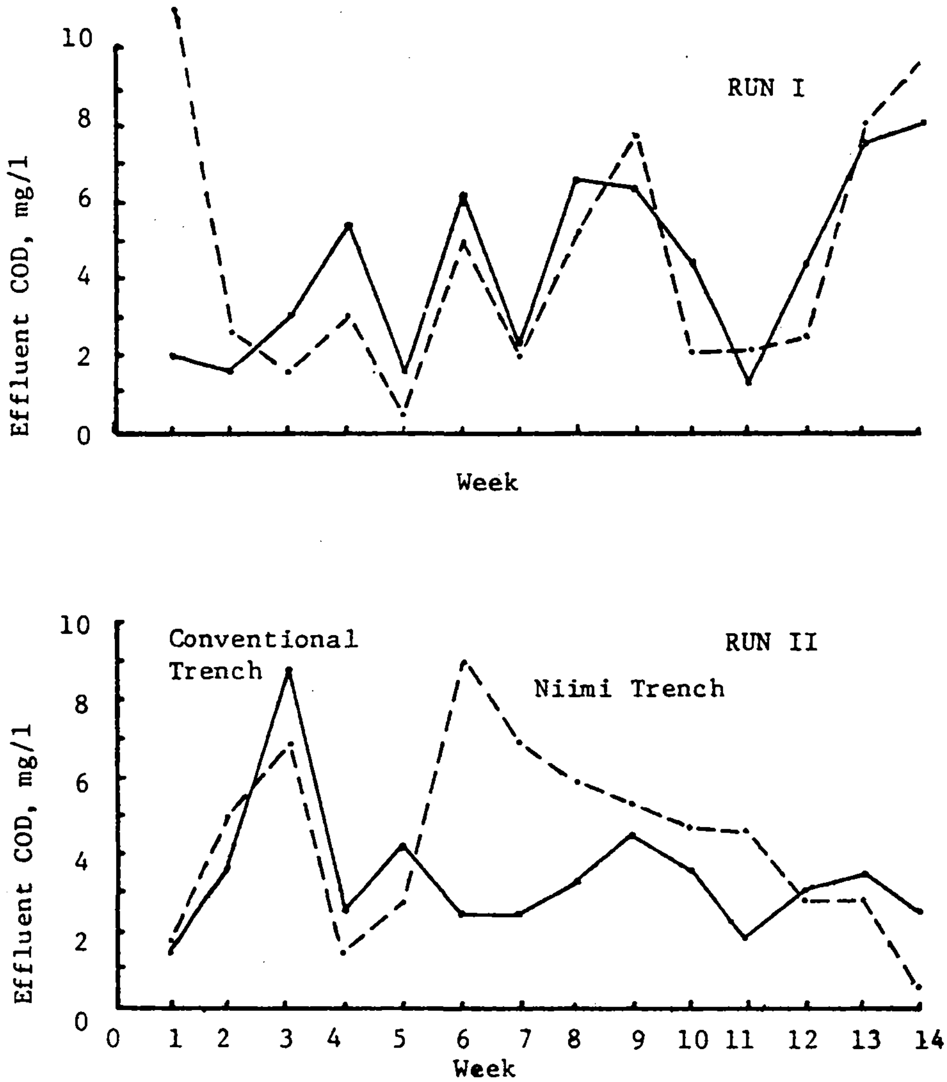


Figure 5. Mean Effluent COD by Week (ports 12-21)

CONCLUSIONS

An experimental study was undertaken to evaluate the performance of a Niimi or capillary siphon trench as compared to conventional gravel filled soil absorption drainage trenches. No statistically significant differences were found between the performance of the two reactors for the soil (heavy clay) and synthetic wastes used except for NO_3-N and Total-N removal during Run II where the Niimi trench was the slightly more effective. The reactors removed 99 percent of the applied COD, 95-99 percent of the applied phosphorus 18-31 percent of the total nitrogen. The hypothesis that the Niimi trench was superior to the conventional trench was not demonstrated. Both systems achieved high rates of COD and phosphorus reduction but had limited effect upon nitrogen removal. Neither system appeared to offer significant advantages over the other at waste loadings characteristics of domestic sewage on Guam.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The mechanisms of pollutant transport and removal in soil during unsaturated flow conditions have not been studied thoroughly. Fundamental research is needed to determine optimum waste and hydraulic loadings as a function of soil type and condition for unsaturated flow treatment system.

2. Insufficient information is available concerning nitrogen dynamics and transport in soils to evaluate soil based treatment systems. Work is needed to quantify denitrification, volatilization, and immobilization dynamics as affected by soil type and moisture levels.

3. The present study should be repeated with domestic sewage for a longer period of time to see when and if the reactors' effluents will stabilize. This will allow a more accurate appraisal of the Niimi system.

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