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The Effect of the Flow Paths of the Wastewater to the Performance of the Vegetative Filter Strip for Phosphorus Removal

축산 폐수 이동경로가 초생대의 인제거 기능에 미치는 영향

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Abstract

The objectives of this study were to characterize the wastewater flow through the VFS, and relate this to the P removal in the VFS. A total of 68 subsurface wells (20~40 cm below the soil surface) and 35 surface wells (0~5 cm), and the application of chloride tracer were used to investigate flow paths and soluble reactive P (SRP) removal from the 21 m wide and 33 m long VFS receiving dairy milkhouse waste. The early chloride breakthroughs in wells in the center of the VFS showed that the milkhouse waste flows preferentially down in the center of the hillslope. The locally saturated area created near the discharge pipe in the center of the VFS accelerates surface flow that contributed to rapid transport of P to the down slope area. Although VFS of 33m long eventually reduced SRP to lower than 0.2 mg/L in most cases, SRP is less effectively removed in the areas where soil saturation occurred. It is suggested that the effort to distribute the wastewater uniformly to avoid soil saturation and reduce the flow velocity need to be considered in new designs.

Keywords : vegetative filter strip, milkhouse waste, phosphorus, soil saturation

I. Introduction

The movement of phosphorus (P) from agricultural lands to surface water can accelerate eutrophication (Sharpley et al., 1993). The most visible consequence of eutrophication is the algal growth in water, which results in odor and taste problems, and also fish kills caused by decreased dissolved oxygen levels (NRC, 2000). Low con-

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centration of P in excess of 35 μg/L are generally associated with the mesotrophic threshold (Vollenweider, 1975), but concentrations as low as 10 μg/L of soluble reactive P (SRP) and 20 μg/L of total P may result in eutrophication (Sharpley and Rekolainen, 1997). Despite increased emphasis on P control, eutrophication is still the major water quality problem of U.S. surface waters (USEPA, 1994; Carpenter et al., 1998; Kleinman et al., 1999), thus continuous efforts are desired.

New York City (NYC) was granted an exemption from EPA's Surface Water Treatment Rule(SWTR, 40 CFR part 141, subpart H) by providing an acceptable plan for the watershed communities to improve environmental quality (USEPA, 1997; NRC, 2000). Approximately 90% of NYC's drinking water supply comes from the Catskill area including the Delaware River (Catskill/Delaware Watershed), while the rest is provided by the Croton River system east of the Hudson River (USEPA, 2001) (See Fig. 1). Ninety percent of the Catskill/ Delaware Watershed is occupied by agriculture and forest land uses, consisting of 350 dairy and livestock farms (USDA-NRCS, 1999). Therefore, P inputs from agriculture are primary concern in NYC's watersheds (NRC, 2000).

Milkhouse waste from dairy farms is one of the primary agricultural P sources. One commonly recommended Best Management Practice (BMP) to treat milkhouse waste is a VFS (Asmussen et al., 1977; Dillaha et al., 1989; Magette et al., 1989; Misra et al., 1996). The VFS is vegetated land designated for filtering pollutants or localized erosion protection (Dillaha et al., 1989). Since the VFS use to treat milkhouse waste was first recommended by Light (1972), only a few studies have evaluated the use of VFS to treat milkhouse waste (Yang et al, 1980; Walter et al., 1983; Schwer and Clausen, 1989). All of these studies reported high P reduction rates of 82%~99% by input-output comparison, but none of these investigated P changes inside the VFS area. Recently, Geohring et al. (2003) focused on distribution and seasonal fluctuation of P inside the VFS. Although Geohring et al. (2003) also observed SRP reduction of 85% and 90% across the filter strip, high SRP concentrations from localized areas in VFS were consistently observed. Surprisingly, the soil in the area of high SRP concentration has the lowest soil concentration P in VFS (Geohring et al., 2003).

Although it is likely that the variable P concentration is related to the flow path of the wastewater as suggested by Turner and Haygrath (2000), the exact location of the flow paths could not be defined accurately in the study by Geohring et al. (2003). In this follow up study we characterize the flow paths inside the same VFS and relate this to the SRP concentrations, and ultimately to removal of P of waste water.

Ⅱ. Materials and Methods

1. Site description

The tracer experiment was conducted on existing VFS at a dairy farm near the watersheds of the Cannonsville Reservoir in the Catskill/ Delaware Watershed (Fig. 1). The 21 m wide and 33 m long filter strip was installed in July 1996, about 200 m downhill from the milkhouse and 70m up from the stream (Town Brook) on

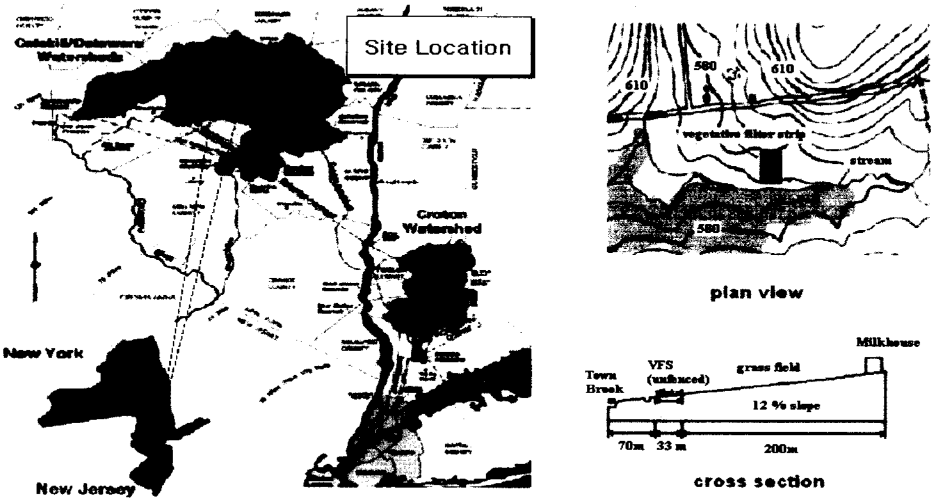


Fig. 1 Location map and geographical condition of site

a 12% slope. The soil in this site is classified as a Barbour series (coarse-loamy over sandy or sandy-skeletal, mixed, active, mesic Fluventic Dystrudepts) which consisted of very deep, well drained soils formed in recent alluvial deposits (USDA-NRCS, 1998). The farm milks about 80 cows per day and produces 1,200~1,400 liters of milkhouse waste each day. The SRP concentration from the milkhouse waste was generally 10~20 mg/L throughout the sampling period. The filter strip was planted with a cool season grass seed mix which includes tall fescue (Festuca arundinacea), orchard grass (Dactylis glomerata), timothy (Phleum pratense), and perennial ryegrass (Lolium perenne L.). The plants in the VFS were overall 80~100 cm high, and there was no adsurd growth of plants observed during the experiment. Milkhouse waste is discharged through one discharge pipe to a 15 m long, 0.5 m deep, and 0.5 m wide graveled ditch, installed perpendicular to the discharge at the top end of VFS. A wooden board is placed across the length of the ditch to uniformly discharge the milk waste across the surface width of the VFS.

2. Wells

Two different types of sampling wells were developed using 4 cm diameter PVC pipes (Fig. 2). The first type of wells (subsurface wells) were designed to capture water at the 20 cm~40 cm depth below the soil surface. Subsurface well pipes are 60 cm long, and have 1.15 cm diameter

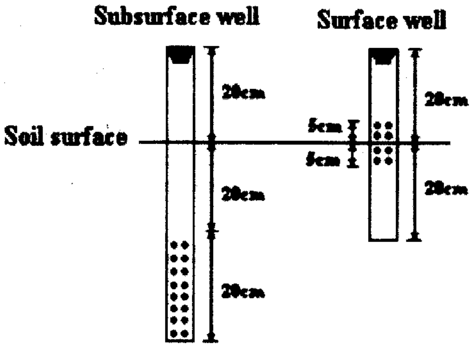
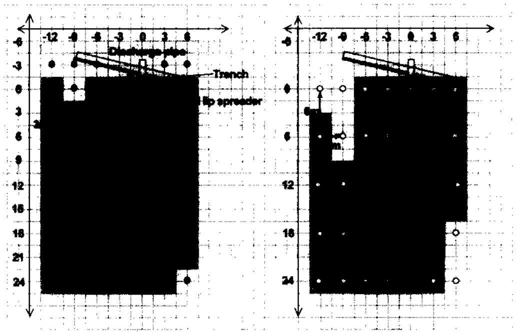


Fig. 2 Sampling well types

perforations in the bottom 20 cm. When installed, the top 20 cm protruded above the soil surface with the remaining 40 cm below the surface. The second type wells (surface wells) was to designed to capture surface runoff and also the shallow subsurface flow to about 5 cm below the soil surface. The 40 cm long surface well pipes have a 10 cm length perforated section in the middle.

For both types of wells, the bottoms were capped and the perforated section was wrapped with textile to allow water flow and prevent soil particles from entering the well. The wells were installed on a 3 m by 3 m spacing. The plan view of the VFS for well locations represented by the (x, y), distance to the origin of the coordinate system is shown in Fig. 3. The convention for labeling the wells was such that the start of the main flow was the origin.



(a) (b)

Fig. 3 The plan view of the VFS for 68 subsurface well locations (closed symbols; a) and 35 surface well locations (open symbols; b) Two types of wells are installed on one VFS, but figured separately for the convenience

The origins (0,0) for well coordinate system was the discharge point of milk waste at the top center of the VFS. Each well was spatially identified by the distance from the origin in the x-, and the y-coordinate direction i.e. (x,y). Later in the result section (Fig. 4), transects, identified as all the wells corresponding to the same x-coordinate, were nominated as T, while rows on the same y-coordinate were R.

3. Well water sampling for SRP analysis

Well water samples were collected approximately once a month between October, 2001 and May, 2002. The average annual precipitation of this area is 1,044 mm, and no major storm event was observed throughout the experimental period. Samples were collected in 240 ml plastic bottles using peristaltic hand pumps. The bottles were placed in a cooler and transported to the Soil and Water Laboratory at Cornell University. All water samples were vacuum filtered through 0.45 μm filter in the lab within 24 hours of collection. The filtrate was stored in a refrigerator at 4℃, and was analyzed within 5 days for soluble reactive (dissolved orthophosphate) P. The analytical procedure utilized an automated ascorbic acid method using an OI Analytical FS-3000 analyzer, and followed standard operating procedures (USEPA, 1984).

4. Tracer experiments

A concentrated chloride solution was prepared to perform the tracer experiment using 20 kg of 80% $CaCl_2$ (Kemira Chemicals Co.) in 100 L of tap water. This mixture was diluted with 400 L of natural water resulting in a final chlorine concentration of 18.4 g/L. A total volume of 500 L chloride solution was applied to the middle of the VFS within 45 minutes for an application rate of 11.1 L/min based on the daily milkhouse wastewater discharge of the farm.

Well sampling began immediately after the start of tracer application so that the rapid transport of chloride in the beginning could be monitored. Well water samples were collected using peristaltic hand pumps at 20~30 minute intervals during the first several hours. The sampling interval was increased to an hour and once in two or three hours after the tank was emptied. Samples were taken three times for the next day following the tracer application and once a day thereafter for 20 days. Water samples were collected with the same procedures as described earlier and wells were completely purged between samplings. Chloride analysis of samples was performed with a digital chloridometer (Buchler instruments). One set of samples from the first day of the experiment was also analyzed for the SRP concentration as described earlier.

Ⅲ. Results

1. Tracer Experiment

In Fig. 3, darker grey colors represent the areas where the changes in chloride concentrations from the well water samples were observed after the tracer application, while lighter grey colors are the areas having water samples in the well but no significant changes in Cl were detected. Dry wells have no color.

The figure simply indicated that the chloride concentrations of water samples increased preferentially in the certain areas. Spatial chloride concentrations in VFS were plotted with respect to time after chloride application in Fig. 4. Note that the intervals of the C/Co scales are different. The observed concentrations at each well were normalized with the applied chloride concentration (C/Co). In Fig. 4, spatial chloride concentrations for the surface wells are shown on the top and subsurface wells are on the bottom at different times. In this experiment, the increases in chloride concentrations were observed first from the wells on transect-0 (T0) for both surface and subsurface wells 30 min after the experiment began. Surface flow spread to the down slope area quickly after 2 h of the application. For subsurface flow, the chloride concentration was extended to the down slope area 3 h after the experiment started. The high chloride concentration observed from the well 18 m away from the trench (Row 18) on transect-6 (first appeared on the figure for 24 h in Fig. 4) was due to chloride transport through a surface flow path to that point. The chloride concentrations were significantly decreased 20 days after the experiment for both flow paths.

Breakthrough curve (BTC) developments for surface wells and subsurface wells in Fig. 4 clearly showed that surface flow increased in chloride concentrations first followed by subsurface flow. The increase in the chloride concentration for subsurface well (0,9) earlier than wells closer to the discharge point such as wells (0,3) and (0,6) indicates that surface flow transported chloride down to this location and mixed with subsurface flow.

This is also the case for the chloride increase for subsurface well (-6, 18) 24h after the application. Although the level-lip spreader for the uniform distribution of wastewater laid on the top of the VFS, flow paths appeared only through

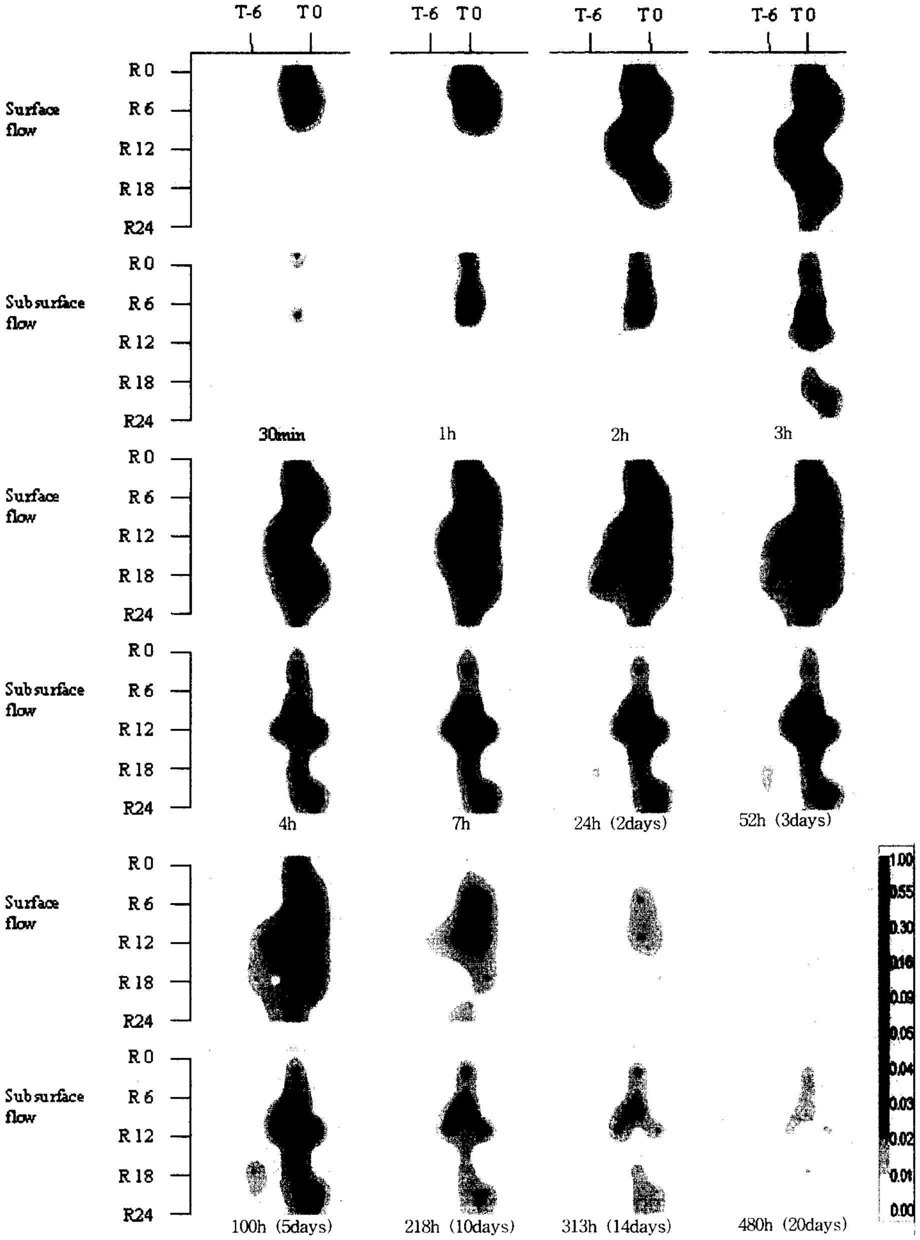


Fig. 4 Spatial Cl concentration over time in the VFS after the tracer.

the center of the VFS on transect-0, implying that the level-lip spreader was not very effective in distributing water uniformly across the top of the filter strip.

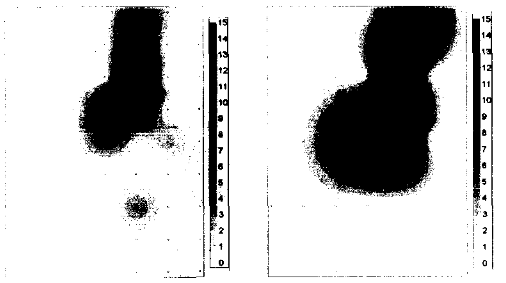
2. The spatial distribution of SRP

The spatial SRP concentrations for subsurface and surface wells measured approximately two weeks before the chloride application (4/07/02) are given in Fig. 5a and b, respectively. The SRP distribution for surface flow was wider and extended further (approximately 6 m down) than that for subsurface one. The highest SRP concentrations were found at wells on transect 0 for both surface and subsurface flows on the 6 m distance from the discharge point with average SRP concentrations of 14.9 and 10.4 mg/L, respectively. The measurement of initial SRP concentration of milkhouse wastewater collected during the day time between regular wastewater discharges on 4/07/02 was 13.1 mg/L, suggesting that SRP concentrations especially for the wells near the discharge point hardly decreased.

Ⅳ. Discussion

1. The comparison of spatial concentrations of chloride and SRP

The spatial concentration of chloride after being applied as a tracer can help better understand the SRP development in the VFS as P is distributed through wastewater flow paths. The spatial distribution of chloride (Fig. 4) and SRP (Fig. 5) showed the similar pattern up to 12 m distance from the trench for subsurface flow and 18 m for surface flow. The highest concentration area between 6 m and 12 m from the discharge point on transect 0 for both subsurface and surface flow also matched. This is an indication that SRP in wastewater moved fast over the surface up to this distance, similar to chloride. However, SRP distribution was not extended further down while chloride distribution almost reached the bottom of the VFS. This implies that SRP in wastewater was effectively removed as flow moved to the down slope area, 12~18 m away from the discharge point. The significant decrease in SRP in downslope area will be discussed later with the flow rate and the velocity obtained from model application, and also with topography in the VFS.

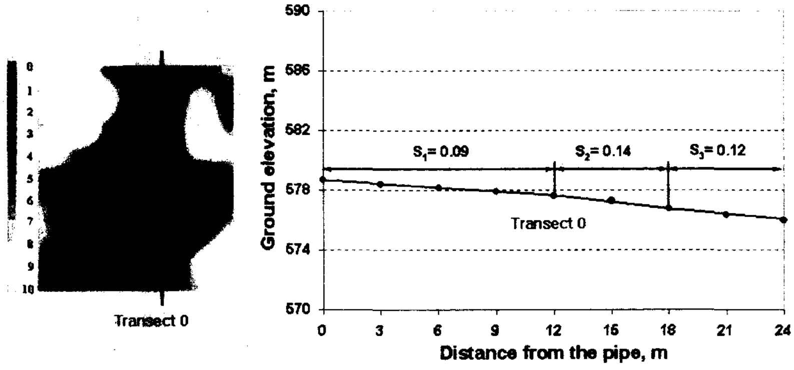


(a) (b)

Fig. 5 The spatial SRP concentration for (a) subsurface flow and (b) surface flow

2. The factors that cause high velocity flow in VFS

As discussed earlier, milkhouse waste was not uniformly distributed throughout the VFS sites, and high velocity (preferential) flow was observed in the center, minimizing P removal by VFS, up to 9~12 m distance from the trench. According to the contour map of the water table inside the VFS (Fig. 6a) measured by Kim et al. (2003), it was shown that the field near the discharge pipe was near saturation showing water tables less than 2 cm from the surface. Therefore, factors that caused the preferential flow could be closely related to the pipe discharge system. This indicated that saturated area near the discharge pipe created by the intensive wastewater discharge caused rapid flow. Therefore, a better discharge method to avoid field



(a) (b)

Fig. 6 (a) Water table contour in the VFS. Numbers in the scale represent the depth (cm) from the surface. (b) The ground elevation chart for 'transect 0' (view from the side)

saturation was necessary to magnify P removal of the VFS. For example, the discharge through two or more outlets could result in a more distributed flow and thus the risk for the localized field saturation could be reduced. The saturated area was also observed downslope (Fig. 6a). The ground elevation survey along transect-0 in Fig. 6b indicates that the slope between 12~18 m distance from the discharge point is approximately 1.5 times steeper than the 0~12 m slope, followed by the flatter area.

This suggested that, different from the saturation near the discharge pipe, the saturated area in the down slope was likely due to the topographic convergence or the decrease in slopes (i.e. decrease in hydraulic gradient), and the problem caused by soil saturation can be minimized during the dry season.

V. Summary and Conclusion

The uniform distribution of milkhouse waste to a VFS was desirable, but apparently difficult to achieve in practice. The tracer experiment indicated that the preferential flow occurred at the VFS in the center of the VFS. The comparison of spatial concentrations of chloride and SRP in VFS implied that SRP in wastewater moved rapidly through preferential flow paths up to 9~12 m from the discharge point, and therefore the removal of SRP by the first 9~12 m of VFS was not effective. The flow velocity significantly decreased thereafter, and the SRP concentration was eventually reduced to below 0.2 mg/L through the 33 m long VFS. High velocity flow was caused by the concentrated discharge of wastewater, and apparently minimized the VFS performance for the P removal. Therefore, the effort to better distribute the wastewater and reduce the flow velocity in order to increase contact time between wastewater and the soil suggested to be considered in new designs.

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