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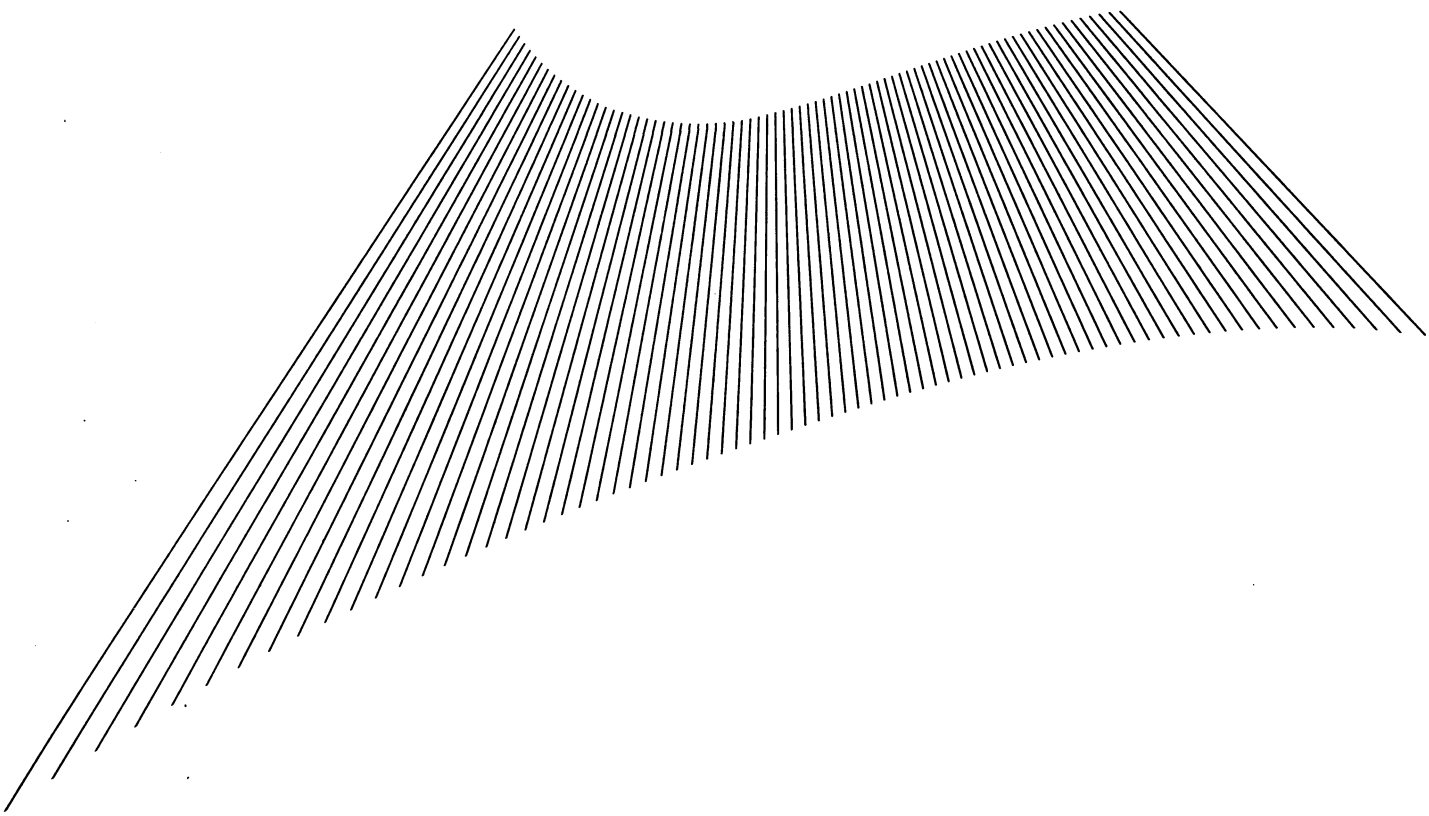
Evaluation of Several Methods of Applying Sewage Effluent to Forested Soils in the Winter



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EVALUATION OF SEVERAL METHODS OF APPLYING SEWAGE EFFLUENT TO FORESTED SOILS IN THE WINTER

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Year-round land application of sewage effluent may be a necessary alternative for northern communities where storage facilities are not possible or are too costly. Sufficient knowledge and adequate materials already exist to engineer systems that will supply effluent to the disposal site during northern winters. Several problems inherent in disposing of effluent on land in northern climates are: (1) limited infiltration of the effluent into the frozen soil, (2) poor distribution of the effluent through the frozen soil mass, and (3) limited renovative capacity of the plant-soil system because of reduced biological activity under low temperature conditions.

Several irrigation systems for effluent application have already been developed for areas with mild winters. Rotating and nonrotating sprinkler systems such as those used by Myers (1966) distribute effluent uniformly, but supercooling from the evaporation of water droplets causes ice to accumulate and stop sprinkler heads from rotating. He also found with low pressure systems that ice did not form, but effluent distribution was uneven.

Effluent has been found to infiltrate frozen forest soils (Nazarov 1969, Sartz 1969, Harris 1972, 1976), however, it may be poorly distributed because of macropore and biopore (openings due to biological activity) channels common to forested soils. These channels conduct and pipe effluent through the frozen soil (Krumback and White 1964, Aubertin 1971, Harris 1972), short circuiting infiltration through the soil mass (Harris 1971).

The present report describes a test of five irrigation systems to: (1) determine their feasibility for use on forest soils during winter, (2) to compare their installation costs; and (3) to determine frost depth, ice accumulation, and effluent distribution patterns in the frozen soil.

Two subsurface systems and three surface systems were studied. The subsurface systems were: (1) subterranean irrigation in which effluent was flooded through underground perforated tile lines, and (2) hole irrigation in which effluent was injected into evenly spaced vertical holes lined with perforated tile. The surface systems were: (1) furrow irrigation in which effluent was channeled through narrow ditches, (2) flood irrigation in which effluent was flooded between levees, and (3) sprinkler irrigation using rotating sprinkler heads (fig. 1). Water quality was monitored under the furrow irrigation plot.

MATERIALS AND METHODS

The study site is located at Fort McCoy, Wisconsin, near the sewage treatment plant. The soil is a Sparta sand (*Entic hapludoll*) which is well-drained and low in available water capacity, natural fertility, and organic matter content. Vegetation is 40-year-old jack pine (*Pinus banksiana*) intermixed with scrub oak.

Chlorinated secondary effluent was pumped to the site by two 7½ horsepower centrifugal pumps through a 6-inch supply main. The main supply line split into 3-inch mains which supplied effluent to individual plots. During winter, the effluent temperature was approximately 2C at the point of discharge to the plots.

The plots were 0.18 ha (0.44 acre) in area. Each plot was irrigated during the frost-free seasons. With the onset of soil freezing, irrigation was stopped on half of each plot so that the effect of antecedent water content on soil freezing could be

measured and compared with water content in the winter-irrigated soils. Irrigation started in October of 1973 and continued for 2 years. The hole and sprinkler irrigation systems were dropped after the first year and the flooding system was started in the second year (fig. 1). Effluent was applied at the rate of 10 cm/week once a week on a plot area basis in all systems tested. Half of each plot was irrigated year-round and the other half during the growing season only.

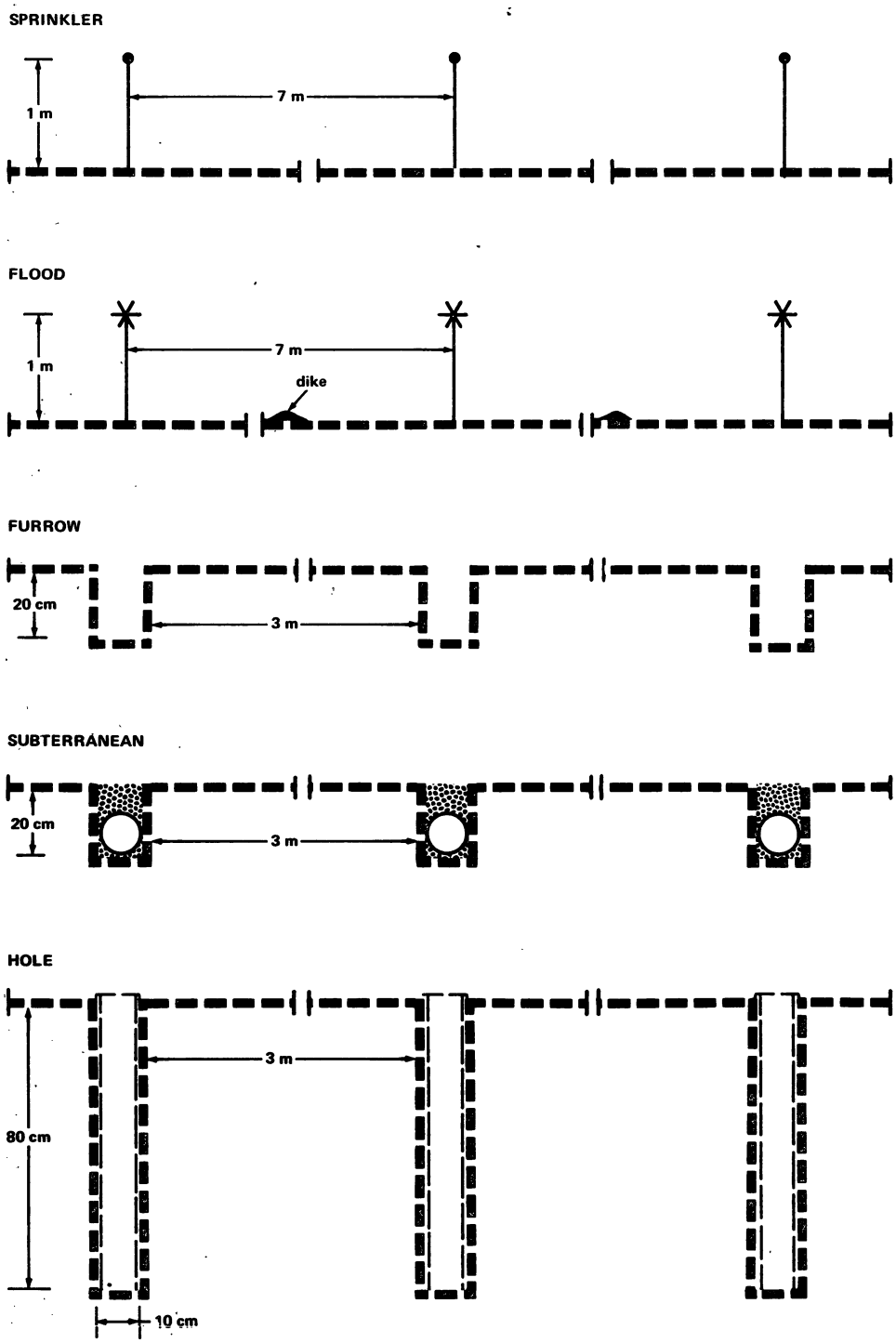

Figure 1.— *Schematic of the five irrigation methods used for winter effluent irrigation.*

Description and Layout of Irrigation Systems

All irrigation system layouts were made as similar as possible to simplify construction and minimize costs. Laterals were equipped with commercial flow control valves at the point of application. Flow control valves deliver the same rate of flow over a pressure range of 4.2 to 8.4 kg/cm^2 (60 to 120 lbs/in^2). This made it possible to apply the effluent uniformly over the plot without the time-consuming balancing of pressure. The sprinkler system was not regulated by flow control valves and was dependent upon system pressure for delivery rate. The flow control valves and sprinklers were spaced so as to deliver 17 mm (0.67 in) of effluent per hour. The description of each irrigation system is as follows:

Sprinkler.— This system was designed for above-freezing conditions. However, it was operated over the winter 1973-1974 to investigate difficulties encountered with sprinkler systems under freezing conditions. Sprinklers were spaced 7 m apart in a square pattern. The sprinklers delivered 17 mm (0.67 in) per hour of effluent at 2.5 kg/cm^2 (35 psi) at the sprinkler nozzle. Materials cost $400/plot or $2200/ha.

Furrow.— A trencher was used to make a furrow 13 cm wide and 20 cm deep. Trees and tree roots made it difficult to slope the furrow edges. The flow rate was controlled at 19 l/min (5 gpm) by the flow control valves. The stream was split at the center of each quarter plot and sent in opposite directions toward each end of the furrow. Furrows were spaced 2 m apart. Materials cost $275/plot or $1530/ha.

Subterranean.— Furrows were dug the same as in the furrow plot, then 10 cm (4-in) perforated plastic pipe was laid in each furrow and covered with soil to the level of the original surface. The top of the tile was 10 cm below the soil surface. Effluent was distributed in the same manner as with the furrow plot. Materials cost $575/plot or $3200/ha.

Hole.— Holes were drilled 0.75 m (2½ ft) deep and 3 m (10 ft) apart in a square pattern. Ten cm (4-in) perforated pipe was then capped and 2.8 l/min (¾ gpm) flow control valves were inserted through the cap. Materials cost $800/plot or $4500/ha.

Flood.— An area 7 m^2 diked with soil borders was flooded from the center. This system was operated the second winter by removing the sprinklers and risers and inserting flow control valves. The flooding test was initiated to develop a two-tier irrigation system using sprinklers during the frost-free season and flooding during the frost season.

Labor is not included in the above costs. Because of tile placement the hole and subterranean systems were slightly more labor intensive than the other systems.

Gandahl type frost tubes (Harris 1970) were installed on a diagonal across each plot to measure any gradients in frost depth that might be due to uneven effluent distribution. Frost tubes were placed alternately adjacent to, and midway between, irrigation laterals to measure the frost gradient between laterals. Frozen soil core samples were obtained down to the frost line with an ice corer (Harris 1972). The core was then sectioned and analyzed for bulk density and water content.

A well for measuring water quality was established in the center of the furrow plot and a control well was established outside the plots. Samples were collected periodically from the wells and the chlorinated effluent holding tank during the winter of 1973-1974. Samples were analyzed for nitrate, total nitrogen, total phosphorous, and chloride. Ground water variation with respect to irrigation was also measured.

RESULTS AND DISCUSSION

Three of the five irrigation systems tested operate satisfactorily during winter. No difficult maintenance problems were encountered with the furrow, the subterranean, or the flood irrigation systems. Distribution of effluent under the sprinkler system became uneven early in the winter as nozzles began to ice and sprinkler heads ceased to rotate. In spite of the icing problem a few sprinklers operated satisfactorily throughout the first winter. An ice layer more than 40 cm deep formed under the operating sprinklers. Icing was also a problem in the small flow control valves on the hole irrigation plot. Water droplets would freeze in some of the small valve openings after each irrigation. For these reasons, the sprinkler and hole

irrigation systems were not run the second winter. Some ice did form on the surface of the flood irrigation plot but the ice did not exceed 5-cm thickness.

Average minimum temperatures for the irrigation periods December 1973 through March 1974 was −11C; and for December 1974 through March 1975−14C. However, temperatures as low as−38C were recorded. Snowfall was below normal for the first winter but above normal for the second winter.

Frost Depth

Soil frost depth was dependent on whether the effluent was applied on the surface or subsurface. Frost was deeper in the sprinkler plot than under other systems but because so few sprinklers operated throughout the winter, frost measurements for comparison with other plots could not be obtained. Frost measurements made on core samples removed from the sprinkler plots showed frost depths greater than those in the furrow plot.

The contribution of heat to the soil system by the effluent can be greatly reduced by exposing the effluent to the air when the effluent is applied on the surface. Frost depth was greater under the surface application systems for both winters (fig. 2). Subsurface application systems resulted in frost depths that were less than in surface irrigated plots. To accomplish this the effluent must be injected several centimeters below the soil surface, which by-passes the soil layers that are most important in renovating effluent.

Effluent placement affected frost depth. Frost depth was usually greatest near a furrow, subterranean tile, or hole and decreased as distance from them increased. Frost depth was partially related to water content and was usually higher near a furrow, tile, or hole.

The effect of antecedent water content on frost depth was measured by comparing nonirrigated controls with the plots irrigated in the growing season and year-round on the furrow and subterranean systems (fig. 3). Both irrigation schedules resulted in deeper frost than the control, presumably due to an increase in heat conductivity of the wetter soils. By midwinter, the frost was deeper under winter irrigation in the furrow treatment. Soil moisture contents were evidently high enough in early winter to maximize heat transfer in both irrigated plots. Frost depth during the later part of the winter was significantly less with year-round subterranean irrigation than with growing season subterranean irrigation. In the subterranean plot the drier soil layer at the surface probably insulated against heat loss. Subsurface irrigation also introduced more heat into the system because the effluent was not exposed to the surface upon application as in the furrow system.

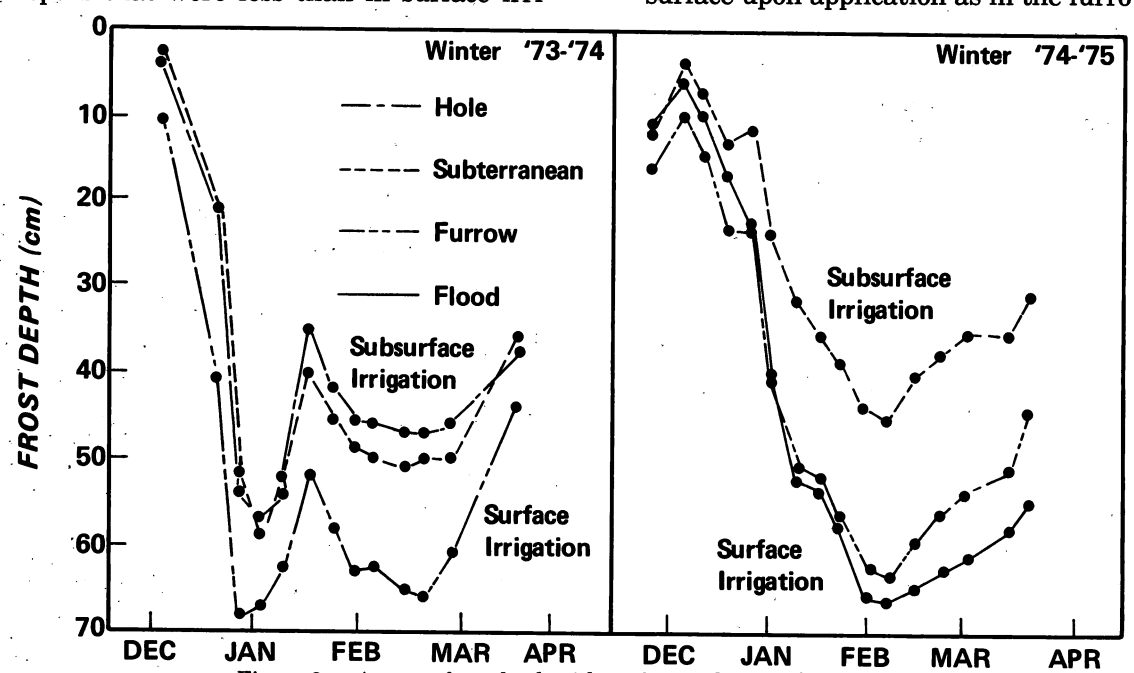

Figure 2.—*Average frost depth with surface and subsurface irrigation.*

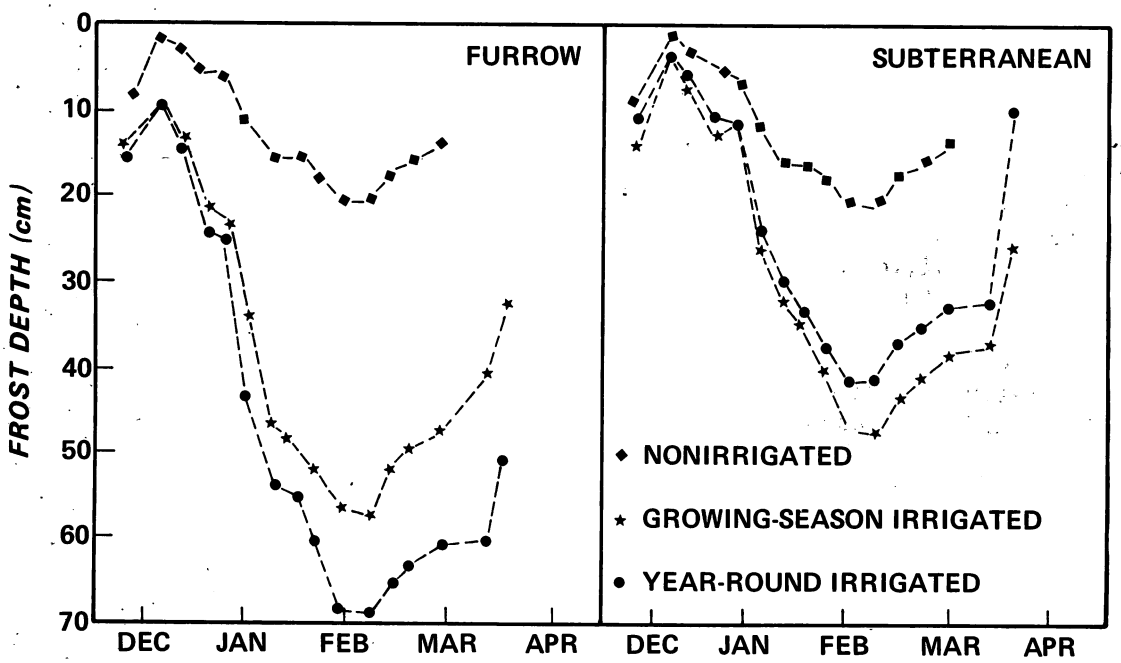

Figure 3.— *Average frost depth among nonirrigated, growing-season irrigated, and year-round irrigated plots for winter of 1974 to 1975.*

This additional heat kept the soil frost from penetrating as deeply as under plots irrigated during the growing season.

Frost Accumulation

Effluent that accumulated as ice is not directly related to frost depth. Although the subterranean and hole plots had essentially the same frost depth, the hole plot had water volume percentages comparable to the sprinkler and furrow plots. This was due to the application method. With the furrow and sprinkler plots, large surface and subsurface accumulations of ice were due to exposure to low temperatures; in the hole plot, ice masses accumulated around the hole.

Accretion of water in the soil mass by freezing is a form of water storage. In this soil, average field capacities varied from 15 percent at the surface to 8 percent in the subsoil. Soil ice buildup continues throughout the winter with irrigation (fig. 4). Water content increased in both the furrow and flood plots at all depths that were frozen. Effluent stored in this way should receive more renovation than effluent leached or piped directly to lower soil depths. However, the overall storage factor is small when compared to the total effluent added. Average stored water above field capacity was 4 to

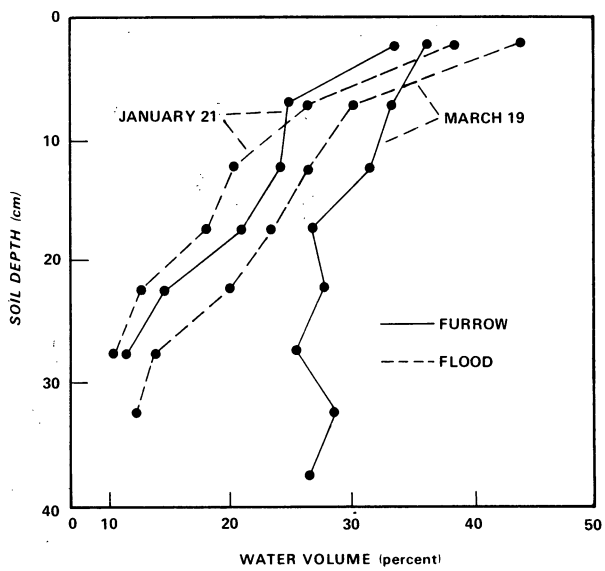

Figure 4.— *Average soil water content for two sampling periods in the furrow and flood plots. Frost depth was 27 and 28 cm for January 21 and 33 and 38 cm for March 19, respectively, for flood and furrow plots, winter of 1974 to 1975.*

8 cm for 1974. This is less than one week's irrigation of 10 cm, accounting for less than 5 percent of the total effluent applied during either winter.

In the winter of 1973-1974, water contents of 33, 42, 44, and 48 percent were found in the surface soil layer of the subterranean, hole, furrow, and sprinkler plots, respectively. Water content decreased with depth until percentages at the maximum frost depth were just higher than unfrozen field capacity values of about 12 to 18 percent. In the winter of 1974-1975, the frost was not as deep or water content as high in the surface soil layer as in the previous year because of the insulating effect of more snow. Water contents of 30, 36, and 43 percent were measured in the surface soil layer on the subterranean, furrow, and flood plots, respectively, in the second winter. Again, water content decreased with depth as in the previous winter.

Effluent Distribution

The distribution of effluent on the soil surface was mainly a characteristic of the application system, however, this relation tends to disappear with depth. The distribution of water in the frozen soil layers at the time of maximum frost depth during the first winter is shown in figure 5.

Injection of effluent in a furrow would be expected to increase the water content more directly beneath that furrow than midway between two furrows. Because of ice buildup and subsequent

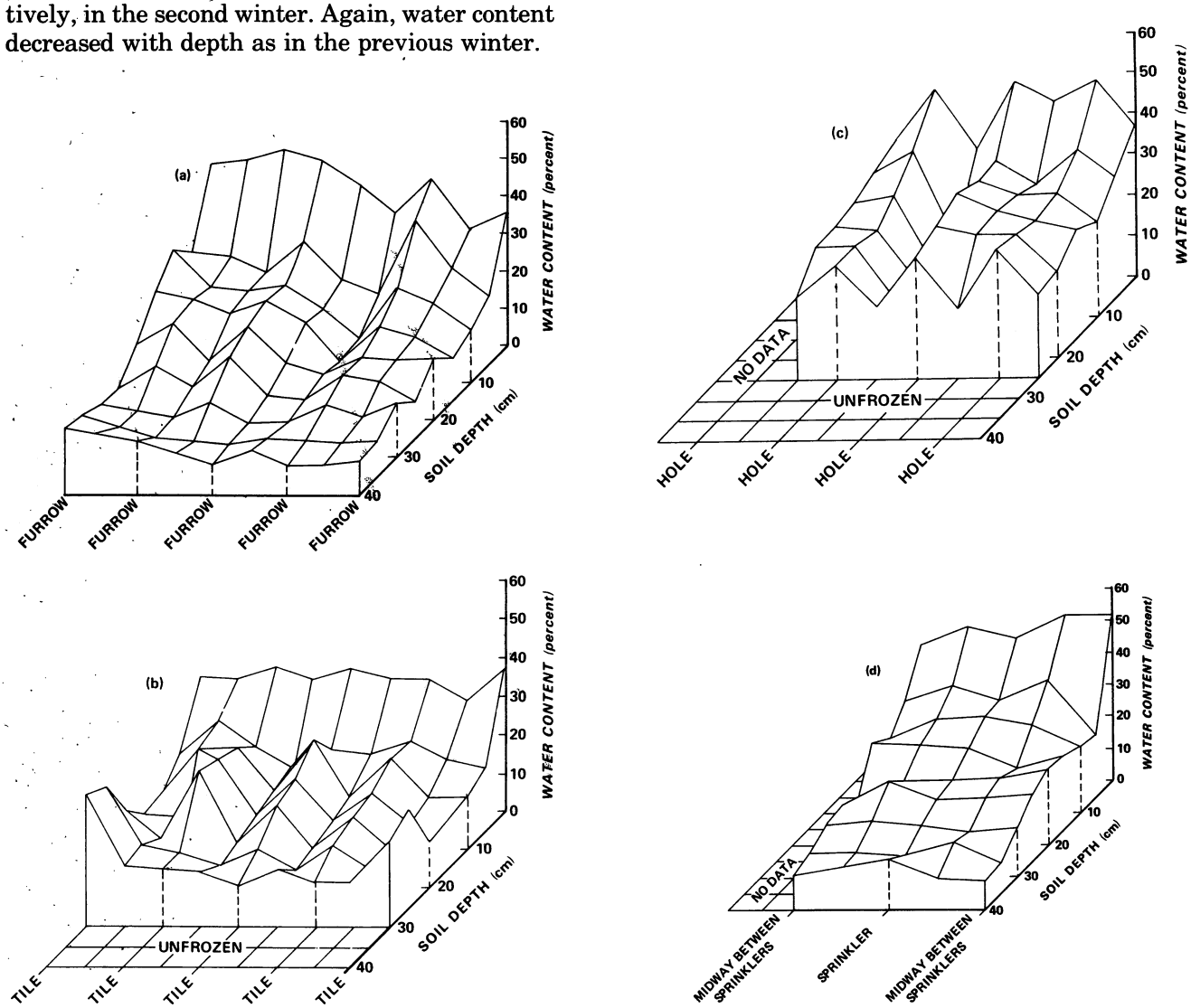

Figure 5.— *Spatial variation of water content with depth in irrigated plots with respect to (a) furrow spacing, (b) subterranean tile spacing, (c) hole spacing, and (d) sprinkler spacing, February 26, 1974.*

flooding between furrows, however, the distribution of water varied greatly (fig. 5a, March 1974). In the flooded areas between furrows the water content (as ice) was higher. The water content did not always decrease with depth. Localized zones of high water content, which had no apparent relation to the way the effluent was applied, were measured at lower levels. In the second winter soil frost was less deep and water content was more uniform with depth.

Many of the frozen soil cores showed ice-enriched areas around large macropores and biopores, indicating that as effluent was being piped through large pores some of it moved by capillary flow into the soil mass. These seemingly isolated areas of high water content do not appear to be associated with movement of effluent to a freezing front.

The distribution of effluent under the tile system reflected the position of the tile (fig. 5b). This effect is more pronounced at the 10-cm depth and lower than at the surface. Surface enrichment must have come mostly from water contributions of snow or rain or capillary movement of effluent toward the freezing front at the surface. Some isolated ice-enriched areas are also evident under this plot, indicating that piping is a universal phenomenon in these soils.

The hole-plot showed much the same pattern as the subterranean-plot except that distribution differences were much more pronounced at the surface (fig. 5c). Distribution of effluent was very uneven in this system due to the horizontal distance the water had to spread through the soil between each hole.

The soil moisture pattern at the surface reflects the distribution around each sprinkler head (fig. 5d). Winter effluent distribution within the soil mass was not much better than in the other systems. However, once a thick surface ice layer is formed under the sprinkler, the distribution of any unfrozen effluent under the ice layer may be quite independent of the sprinkler pattern.

The 1974 to 1975 distribution patterns, because of shallower frost, were not as descriptive as the previous year. However, frost depths were still uneven indicating that piping is a major source of effluent infiltration. The flood plot showed some of the same distribution patterns as the sprinkler plot.

The ultimate distribution of effluent depends largely on a combination of initial distribution pattern and a secondary pattern due to effluent being piped through the soil by large macropores and biopores. However, movement to a freezing front under temperature gradients also has an effect on distribution with depth (fig. 4).

Effluent distribution will change from winter to winter as the plot undergoes natural modification under the imposed ecosystem. This was well demonstrated in the furrow plot which had a pattern more similar to the subterranean plot in the second winter. There was no vegetation or leaves in the furrows the first winter and the channels quickly froze decreasing permeability to the point where effluent overflowed and flooded between the furrows. Grass and dead leaves accumulated in the furrows over the second year of irrigation. This accumulation combined with a deeper snow cover, kept the furrows partially unfrozen during the winter, resulting in very little overflow between furrows, and more vertical infiltration.

Water Quality

Although an in-depth water quality study was not carried out in this study, the monitoring well in the furrow plot indicates that mobile ions such as nitrate and chloride will move readily through the soil (table 1). With the low soil temperature and no vegetative uptake, renovation of the nitrogen in the effluent is not expected, and in fact did not occur. Since the storage of nitrogen, particularly nitrate, in the soil is so small, effluents must contain small amounts of nitrogen to prevent contamination of ground water. Phosphorous was readily absorbed by the soil, so it should not be a problem with winter irrigation.

Table 1.— *Average nutrient values for effluent and wells at Fort McCoy, Wisconsin, winter of 1973 to 1974*

Item	Nutrient values			
	NO_3-N	Total N	Total P	Cl
	ppm			
Effluent	3.00	4.26	1.47	6.4
Control Plot Well	0.44	0.82	0.29	3.2
Furrow Plot Well	3.60	4.65	0.20	6.1

RECOMMENDATION BASED ON INSTALLATION COST

Because material costs have changed so rapidly, only relative costs are meaningful for each system. The furrow and flood method would be most economical to use. However, if the flood system were combined with the sprinkler system the cost would be only slightly more than the sprinkler system since almost the same hardware could be used for both. This combination would be good for distributing effluent year around. Besides diking between sprinklers some additional hardware would need to be added to the sprinkler uprights for easy conversion. Labor and operational costs were not measured or evaluated.

SUMMARY AND CONCLUSIONS

Sprinkler, furrow, and flood irrigation systems expose the effluent to the prevailing weather resulting in heat loss, deeper soil frost, and surface ice accumulation. The subterranean and hole irrigation systems inject the effluent below the soil surface decreasing heat loss from the effluent which results in shallower frost penetration.

Distribution of effluent in the frozen soil mass was uneven for all the irrigation systems. Closer spacing between irrigation laterals should improve effluent distribution for the furrow and subterranean systems but may not be cost effective. Distribution was a function of the surface wetting pattern, piping due to macropores and biopores, and movement due to temperature gradients. Large macropores and biopores transport water into the subsoil by-passing surface horizons. This one phenomenon may account for the large volume of effluent percolated through a frozen forested soil during winter irrigation.

Nitrate which moves readily through the soil appears to be the limiting factor in winter irrigation. Only effluent with low nitrate concentrations should be used for winter irrigation. Phosphorous renovation seems to be adequate. This is probably true for most of the readily adsorbed chemicals and filterable solids in the effluent. Research on survival of pathogens in the winter will need to be studied. Where TSS, BOD, and phosphorous removal is fairly restrictive for stream discharge, winter application to forested soils may be a better solution.

A flood or furrow system would be the most economical to install. The best year-round effluent distribution is a two-tier system using sprinklers for the growing season and flooding for winter irrigation. Where icing and frost penetration is critical, subterranean irrigation should be considered. Whichever system is used will depend somewhat on the site management requirements.

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OXFORD: 114.12:U628.36. KEY WORDS: Soil water renovation, infiltrations, soil heat loss, soil water movement, effluent distribution.

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