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Land Treatment of Wastewater by Overland Flow for Improved Water Quality

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Introduction

The United States and numerous other industrialized countries face the apparently conflicting needs of environmental quality and energy requirements. The neglect of either would certainly result in catastrophic problems. The impacts of allowing pollution of the environment or of needless use of power supplies are staggering, and careful assessment leads to the conclusion that total regard for the environment and satisfaction of energy needs is an impossible goal. As true as this conclusion may be, both problems should and can be approached with a similar philosophy, for both problems can be classed with others as problems of finite resources. The world has acutely felt the reality of the finite supply of fossil fuels so vital for production of energy and synthetic materials. It has also realized the finite nature of food production. To a somewhat lesser degree, the industrialized nations have realized the finite nature of the diluting capacity of clean air and water or the resiliency of numerous ecological processes.

It is our hope, however, that some of the present adversity experienced by the industrialized world in food and fuel will point to the more subtle problems of environmental quality. One such area in which progress, although slow, is being made in the United States is the recycling of nutrients from wastewater into soil via land treatment.

This paper presents an overview of land treatment of wastewater; a somewhat detailed development of the overland flow system of treatment, which is probably the least understood mode of land treatment of wastewater; and possible modifications of current concepts of overland flow treatment for improved water quality.

Land Treatment Systems

What is Land Treatment of Wastewater?

Land treatment as opposed to land disposal of wastewater is a method whereby wastewater is applied to land in a controlled quantitative manner to achieve the removal of various polluting fractions of the wastewater.[1] The source of wastewater can be industrial or municipal, and treatment before land application can vary from simple screening to secondary treatment and disinfection. The particular combination is dictated by factors such as the type of waste, facility location, and degree of treatment desired.

As with conventional wastewater treatment systems, design and operation of land treatment systems depend upon a number of factors such as source of wastewater, facility location, regularity of flow, and construction cost. Common systems familiar to the sanitary engineering profession are trickling filter, extended air, and anaerobic lagoons. Land treatment systems that are becoming equally familiar to the environmental engineer are slow infiltration, rapid infiltration, and overland flow.[2]

In the rapid and slow infiltration systems, wastewater is renovated by the soil, plants, and microorganisms as it moves through the soil profile. The slow infiltration system is normally an integral component of an agricultural operation.[3] Rapid infiltration systems are usually operated separate from agriculture and are on thick deposits of sandy or coarse gravelly soils.[4] Overland flow systems are somewhat different in that most of the water flows over a relatively impermeable soil surface and the renovative action is more dependent upon microbial and plant activity.[5] Classification and operation of land treatment systems in these categories are based upon their different hydraulic characteristics. Such an approach has been an improvement in land treatment concepts; in the past there was a tendency to believe that only a medium-textured soil that would allow sufficient but not rapid infiltration while maintaining aerobic soil conditions was necessary for a successful land treatment system. The development of rapid infiltration and overland flow treatment systems has enabled both very porous and rather impermeable soils, as well as medium-textured, permeable soils, to be of value in properly designed and operated wastewater treatment systems.

Mechanisms for Pollutant Removal

Regardless of which land treatment system is chosen, the major pollutants normally are nitrogen, phosphorus, trace elements, and oxygen-demanding materials. These water pollutants are, of course, the major components of fertilizers and soil amendments that are necessary for food production. Recycling them into the soil can save on fertilizer consumption as well as improve water quality. In general, the pollutant materials are removed by soil, plants, or microorganisms. The particular mechanisms for removal vary with the system. A summary of the mechanisms involved follows, but these highlights of treatment are very brief. The actual treatment of wastewater by any one of the three methods requires management based on known operational principles to maximize the renovation of wastewater. Many variables, such as the cover crop, wastewater characteristics, and weather, cause variation in the operation on an unscheduled basis. The treatment of wastewater via a recycling mode is no less complicated than any other. Its advantage is that it works and it recycles rather than consumes resources.

Nitrogen

Of the major pollutants, nitrogen occurs in the most forms. It can be removed in major quantities by the soil, plants, or microorganisms (Fig. 18-1); but a removal mode may be important in one system but not in another. For instance, denitrification is of paramount importance in a rapid infiltration system, because while great quantities of water are passed into the soil, the plant system is only capable of removing a very

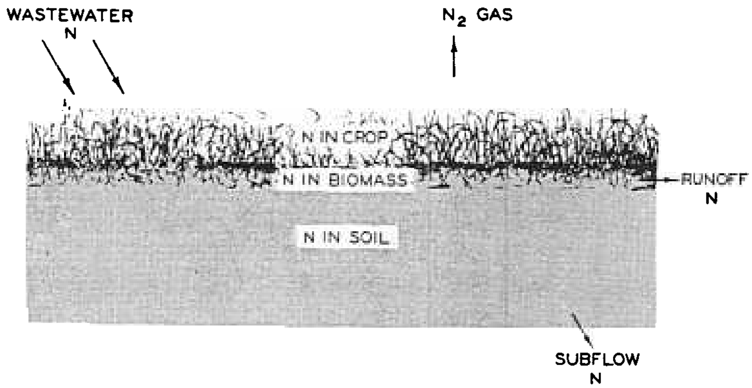


FIG. 18-1. Schematic diagram of nitrogen in overland flow treatment of wastewater.

small fraction of the applied nitrogen.[6] On the other hand, denitrification is of relatively low importance in slow infiltration systems (often referred to as crop irrigation systems), where plant intake removes considerable quantities of nitrogen.[7] Soil adsorption and incorporation of nitrogen into organic matter are also important in slow infiltration systems. Overland flow systems are intermediate in that plant uptake, denitrification, and soil and organic matter incorporation are all important.[8]

Phosphorus

Phosphorus neither appears in the varied forms nor has the removal modes of nitrogen. In particular, it does not have the microbially mediated gaseous loss. Phosphorus removal in rapid infiltration systems is primarily a soil adsorption phenomenon. The somewhat low surface areas of the coarse-textured soil for adsorption of phosphorus is compensated for by the thickness of the soils used in rapid infiltration systems. In addition, water is often forced to move considerable distances in a lateral direction to accomplish a higher degree of treatment. Slow infiltration systems are the best for phosphorus removal for in these systems there is an intimate contact of a relative small amount of wastewater with the high surface area of medium-size soil particles.[9] Overland flow systems have the poorest combination of conditions for phosphorus removal.[10] The soil contact is limited to the soil surface area and the residence time on the soil is normally less than 24 hours. However, phosphorus appears to be removed by the pronounced surface organic layer on overland flow slopes, and this layer can be turned under by plowing in order to take advantage of the fixing capacity of the heavy-textured soil.

Trace elements

Trace elements are removed in much the same manner as phosphorus in that they are absorbed by soil and organic matter. They are also removed by plants, although to a much smaller degree than is phosphorus. Yet, even small amounts can be toxic to the plants, and, in some mismanaged systems, trace elements could increase to the point that the site could no longer be used.[11] As with phosphorus, the soil thickness of rapid infiltration systems allows for more adsorption of trace elements. The slow infiltration systems, however, appear to have the greatest capacity for removing trace elements because of the high surface area contact with the wastewater. While overland flow is limited by soil contact, trace elements are readily fixed by organic material and the surface organic layer of overland flow systems has been found to be very efficient in removing trace elements. As with phosphorus, this layer can be plowed under to take advantage of the fixing capacity of the heavy-textured soils.

Oxygen-demanding substances

In most cases the oxygen-demanding substance is organic material and is removed quite well by all methods of land treatment. The material is first physically filtered as it passes through the soil or grass cover and then decomposed by the soil microflora. Part of the organic material may, however, be more resistant and contribute to an increased organic matter content in the upper layer of soil.

Overland Flow Systems

Design and Operational Description

As was stated earlier, overland flow treatment systems are located on soils of low permeability. This low permeability may result from a number of factors, but most commonly it is either a heavy-textured soil or a soil containing a barrier within the upper three feet. In addition to low permeability, a slight slope is required; slopes up to 8% are generally satisfactory. The slopes are covered with vegetation and normally are 150 to 200 ft. in length with collection channels located at the bottom of the slope.[12] A schematic of an overland flow system is shown in Fig. 18-2. The water is applied at the upper end of the slopes and flows as a sheet over the soil surface and through a surface organic mat into the collection channels. The renovated water then flows to a central channel where the water quality can easily be monitored (Fig. 18-3). The renovated water can then be used for a host of purposes varying from industrial cooling to groundwater recharge.

Operationally, overland flow systems have slow rates of application; volumes are normally

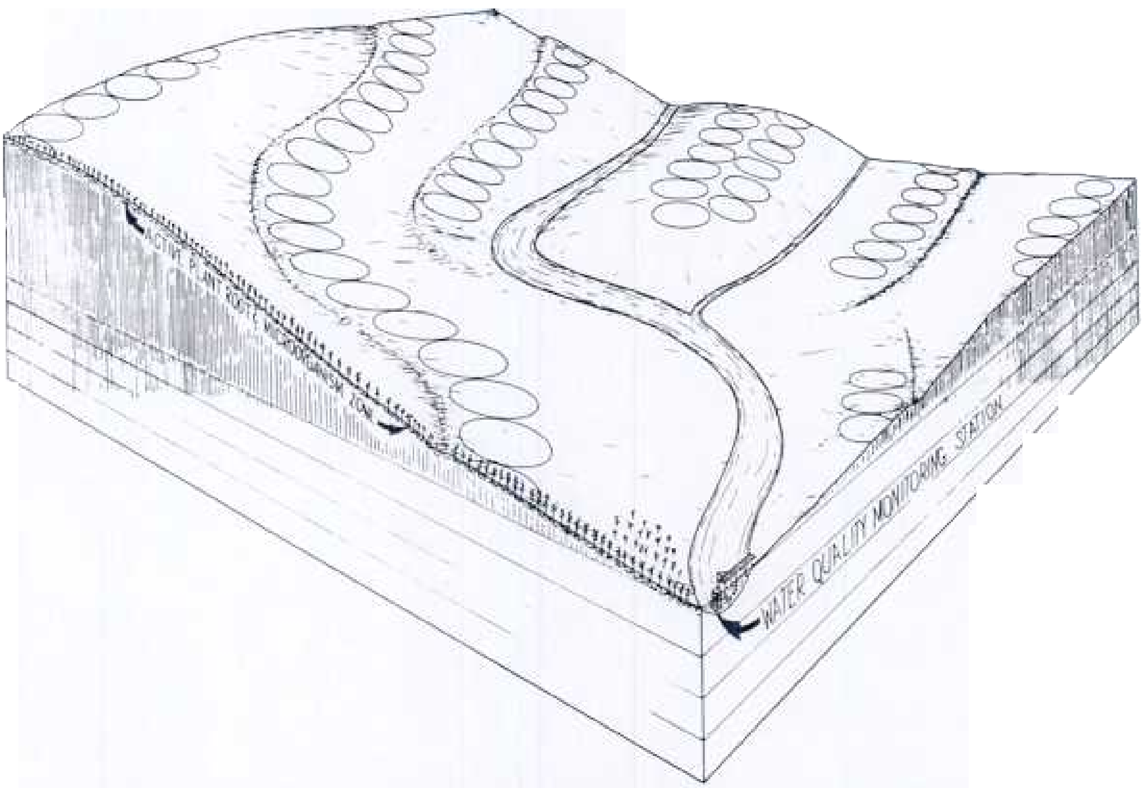


FIG. 18-2. Schematic diagram of an overland flow system. Circles show areas of wastewater application

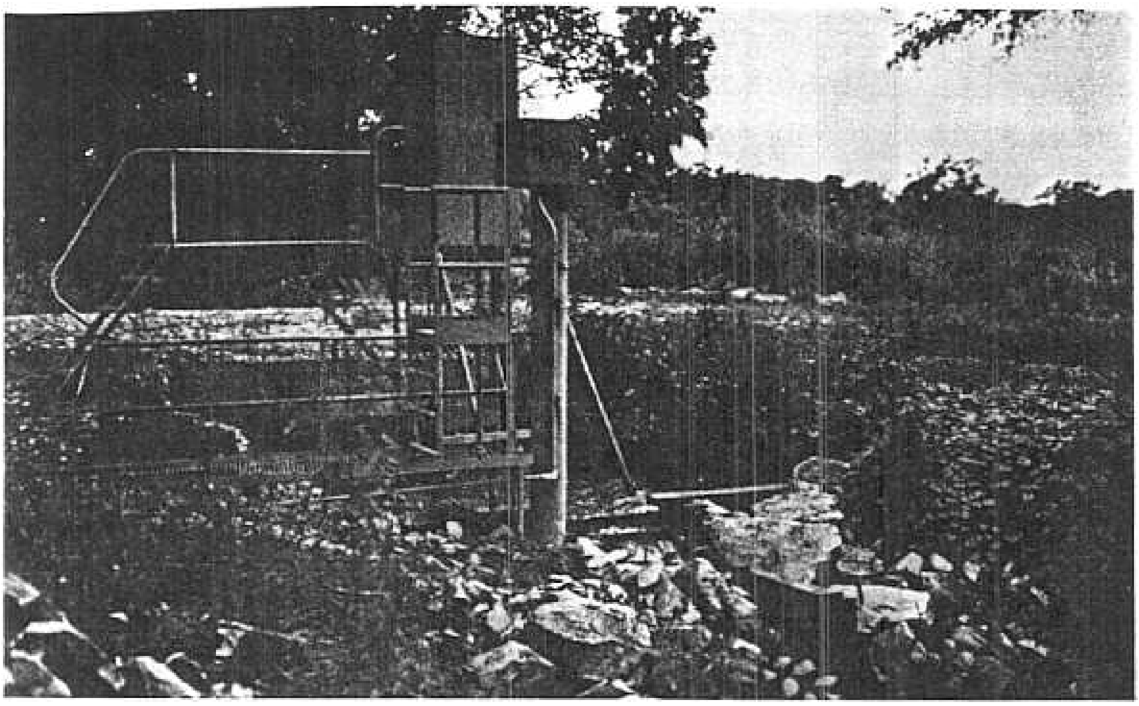


FIG. 18-3. Water-monitoring site for treated water leaving the overland flow treatment site.

less than ½ acre inch per day, and application rates vary from 6 to 18 hours. However, wastewater can be applied on 4 to 6 days per week giving a weekly application of 2 to 3 acre inches. These rates compare favorably with slow infiltration systems. High rates of application invariably cause poor treatment.

Mechanisms of Overland Flow Treatment

The fact that overland flow treatment of wastewater removes a very high percentage of the applied nitrogen is somewhat surprising. The wastewater does not flow into the soil where nitrogen could easily be adsorbed on the clay particle surfaces or be removed by plant uptake. In addition, the fact that the surface water is aerobic and would tend to eliminate the possibility of denitrification. However, upon further investigation other conditions make nitrogen removal seem quite likely. The organic layer on the soil surface as well as the shallow root system of the flooded cover crop usually removes from 50 to 75% of the applied nitrogen. Significant denitrification appears to be responsible for the remaining nitrogen removal.

The intricate way in which denitrification and nitrification appear to function on an overland flow system is one of the most interesting aspects of this intriguing system. The water film and underlying soil seem to form an aerobic-anaerobic double layer similar to that found in rice fields or marshes.[13] In the overlying water film and organic matter, aerobic processes can occur, and ammonium is nitrified to nitrate (Fig. 18-4). In the underlying anaerobic zone, the nitrate is converted to gaseous nitrogen via denitrification.

The redox potential at which denitrification for a soil is active has been determined with a consideration for pH. Fig. 18-5 depicts the results of redox measurements on an overland

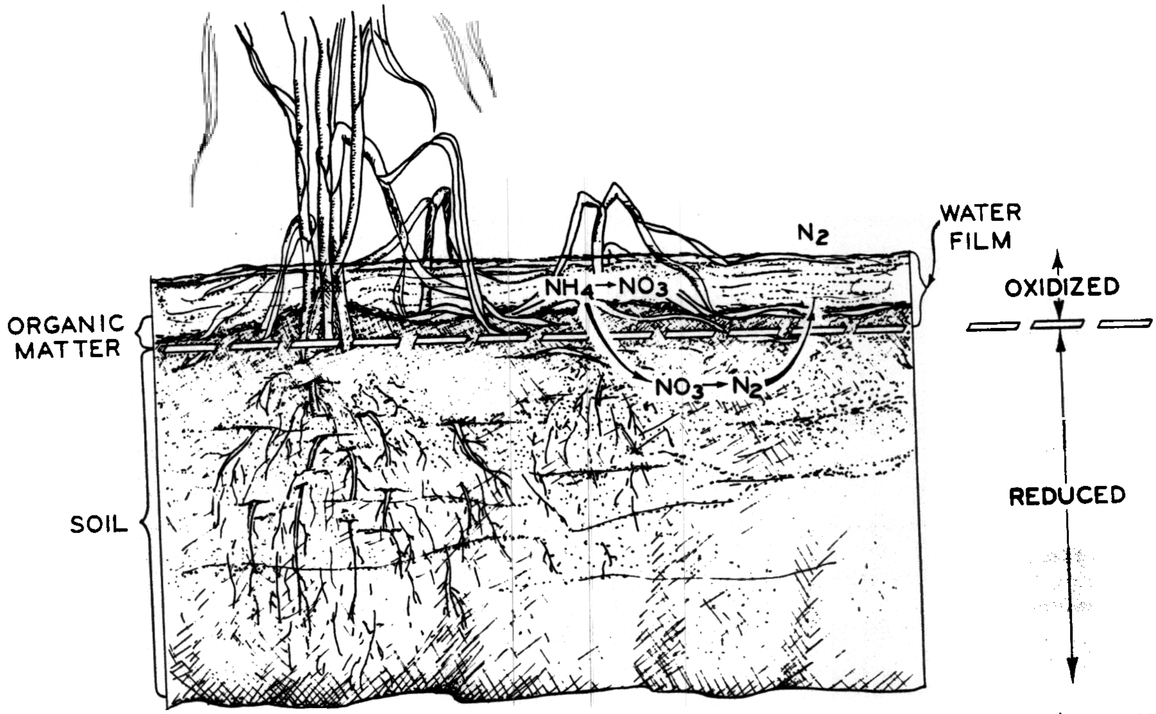


FIG. 18-4. A schematic diagram of conditions that would allow both aerobic and anaerobic processes to occur in an overland flow system.

flow model.[14] The redox potential did not reach an oxidized level during wastewater application at 5 mm depth; the presence of an overlying aerobic layer was demonstrated by oxygen in the water and rapid nitrification of ammonium to nitrate. Positive proof of substantial denitrification has not yet been obtained, but the Waterways Experiment Station is presently conduct-

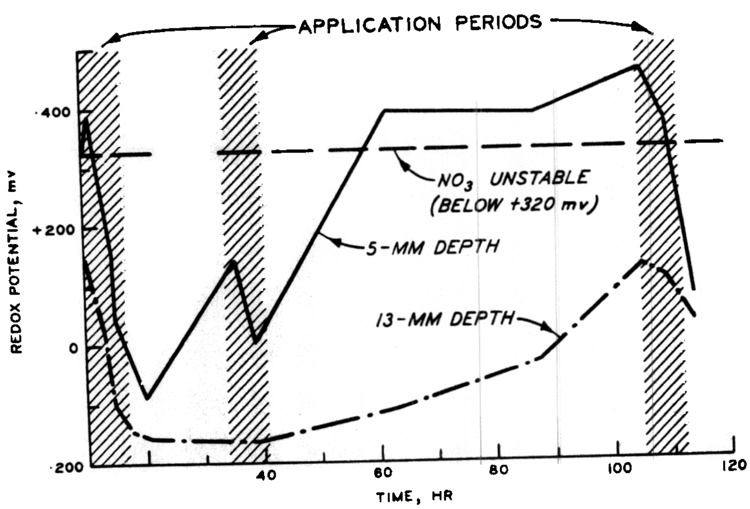
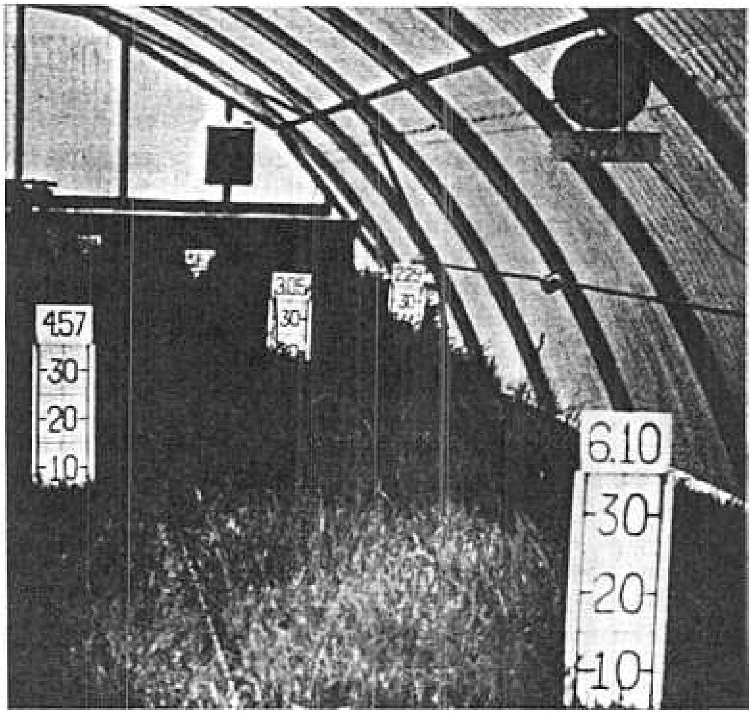


FIG. 18-5. Redox potential of a Susquehanna clay during a wastewater application-drying cycle.

Fig. 18-6. Wastewater model 43 days after start of treatment. Grass height reached 20 to 40 cm in the first 3.05 m of treatment; practically no increase in height and zero nitrogen content in surface water beyond 4.57 m.



ing studies that should yield such proof. To date the evidence is that denitrificating conditions and substantial losses of nitrogen are associated with both field and model overland flow systems.

Nitrogen removal by grass on overland flow is also an interesting phenomenon in that a grass-growth gradient is established down the slope. This gradient has been observed on slopes from 180 feet long in the field to 18 inches in the greenhouse. It appears that in both field and laboratory systems that are functioning properly, the nitrogen concentration of wastewater is reduced to 1 or 2 ppm at approximately two-thirds of the slope's length. Since grass is very responsive to nitrogen, a growth gradient associated with the decreased nitrogen content is established (Fig. 18-6).[15]

Phosphorus and Trace Element Treatment

Since phosphorus removal via land treatment is best when the wastewater is in close contact with the surface area of clay particles as it moves through the soil, overland flow would intuitively seem to be the poorest method of phosphorus removal. As was stated earlier, this is in fact true; wastewater flowing over the soil surface does not have extensive contact with the iron and aluminum compounds of the soil that normally fix massive amounts of phosphorus.

One could, however, suggest that the less-than-complete removal of phosphorus was a result of the reducing soil conditions and related very little to the soil contact phenomenon. Such a view could be supported by the fact that reduced soils often have more available phosphorus than oxidized soils.[16] While this fact is well known and the principal is used by American rice farmers, the situation is not quite that clearcut. Reduced soil seems to have a greater capacity to fix phosphorus, although the amount of soluble or available phosphorus up to 1 ppm may be higher under reduced conditions. This condition has been attributed to a difference between the fixing capacity and surface area of ferric oxide, prevalent under oxidized conditions, and a gel-like hydrated ferrous oxide or ferrous hydroxide prevalent under reduced conditions.[17] Under this hypothesis the ferric oxyhydroxide with its tight binding but low surface area characterisitcs is prevalent in an oxidized soil, and phosphorus is readily removed to very low concentrations from a diluted solution. However, if the liquid, interstitial, or overlying water concentration of phosphorus becomes greater than approximately 1 ppm, the surface area or fixing capacity of the ferric oxide is exceeded. On the other hand, under reduced conditions, they propose that neither the gel-like hydrated ferrous oxide nor ferrous hydroxide fix phosphorus so tightly, but its large surface area results in a substantial fixing capacity. Thus under reducing conditions, a soil will remove more phosphorus from a solution with greater than 1 ppm phosphorus than would be oxidized soil.

Wastewater is the kind of high phosphorus solution that would possibly exceed the fixing capacity of a thin layer of oxidized soil. If the reduced soil is behaving as reported (see note 17), the soil contact rather than fixing capacity would appear to be the reason for somewhat less-than-complete removal of phosphorus by overland flow treatment. In addition, phosphorus appears to be removed mainly by the surface organic mat in overland flow models that receive secondarily treated wastewater. This would indicate that only a fraction of the phosphorus was actually interacting with the soil and would therefore not be capable of saturating the soil's fixing capacity for phosphorus. This point is not yet resolved, but research currently being conducted should do so.

On a more practical basis, it has been shown that greater than 80% of the phosphorus in raw wastewater can be removed by overland flow if stoichiometric amounts of $Al_2(SO_4)_3$ are added before the wastewater is applied to the slopes.[18] Similar results have been found with secondarily treated wastewater by C. R. Lee of the Waterways Experiment Station, Vicksburg, Miss. If this scheme was used, the iron and aluminum phosphates could be periodically plowed under and fixed by the reduced clay soil.

Trace element removal by overland flow is very good, greater than 90% for all and greater than 98% for some heavy metals.[19] This rather high removal is attributed to the surface organic mat where most of the heavy metals in particular are bound. This is not surprising since trace elements are known to be very reactive with organic matter in agronomic soils. As with phosphorus, the surface concentration of trace elements could be reduced periodically by plowing that layer under. Although the reduced soil condition might cause certain heavy metals to be more mobile, it is the authors' opinion that this would be a minor problem in the heavy-textured soils with high organic matter content that are used for overland treatment.

Possible Modification of the Overland Flow Concept

Application to Rice Fields

Since the soil surface of an overland flow treatment system is chemically and biologically very similar to a rice field, a logical question is whether overland flow can be incorporated into rice production.[20] From a mechanistic viewpoint, it would appear that a shallowly flooded rice field would remove nitrogen, phosphorus, and trace elements very well. The diffusion distance through the water column would be five to twenty times greater than in a normal overland flow system, so the residence time should be equally increased.

The wastewater could not contain high concentrations of toxic substances, and it would appear that the wastewater would need to be secondarily treated and disinfected. Such a wastewater would eliminate rather obvious odor and public health problems.

It has also been suggested that rice so grown should be used for consumption by humans only after some processing step that would definitely eliminate any possibility of pathogen transfer.

There are also certain agronomic problems that would have to be addressed, such as the potential growth of algae associated with the wastewater and the use of pesticides on rice. However, when once considers that in rice-growing areas of the southeastern United States, water cost is roughly 20% of the production cost of rice and that in many areas the use of massive amounts of groundwater for rice production is causing ecological concern, the concept would appear worth pursuing in a vigorous manner.

Application to Marsh Areas

The marsh ecosystem also has many similarities to the overland flow mode of treating wastewater. The potential of recycling nutrients through plant and microbial populations in a marsh is great. In these systems organic waste could probably be assimiliated in a satisfactory manner. Quantities of substances such as heavy metals would have to be low to avoid accumulation to toxic levels in the ecosystems. Additionally, nutrient stimulation might increase the organic litter layer so rapidly in certain marshes that the elevation of the marsh would rise enough above the water table to cause death to the dominant plant species of the marsh. Thus application rates would have to be adjusted to avoid excessive stimulation of growth.

An interesting possibility for a marsh system would be to establish a marsh with dredged material and accelerate its establishment with nutrients from wastewater. However, this particular idea would have several obvious problems, one of which would be that a thick plant cover is required for an overland flow system. Another would be that normally artificially created marshes are small in size relative to the area needed for a moderate-sized wastewater treatment system.

Combined Forage Grass-Pulp Forest System

In such a system trees that were water tolerant and fast growing would be selected to grow with somewhat shade- and water-tolerant forages. A combination that would appear to have promise would be cottonwood trees and reed canary grass. The cottonwoods could be spaced wide enough apart to allow forage harvesting and adequate sunlight. A slight ridge could be raised for the trees or they could be planted on a normal slope.

A similar combination of forages and agronomic plants might be possible if ridges that would allow aerobic soil conditions were used for the agronomic plant. The many ramifications of such a concept, including plant disease, competitiveness, and harvesting methods, would have to be evaluated. Yet it would appear that there might be a possibility of increasing the productivity of many rather infertile soils while treating wastewater to advanced levels.

Fiber might also be produced from an overland flow system by a plant similar to kenaf. Such a concept has the appeal of avoiding any pathogenic or toxic metal problems related to human consumption. However, kenaf requires at least moderately aerated soil. The authors do not at this time have a good candidate for a thick-cover fiber crop that will tolerate reduced soils. If, however, a productive use could be found for plants such as *Phragmites communis,* a really excellent system of recycling could be designed.

Chemical and Physical Filters

Some of the attributes of an overland flow system could be used in special situations such as removing the bulk of the organic load before waste was applied to a water hyacinth lagoon for nutrient stripping. Such an approach would appear to have promise for certain cannery wastewaters. An overland flow system might also function quite well in physically and chemically removing suspended material and nutrients that may pass from land disposal areas for dredged material.

Use in Recreational and Rest Areas

Another possible modification is not with the overland flow concept, but with the type of wastewater. Recreational areas such as reservoirs, national parks, and highway rest areas have rather seasonally and daily variable wastewater loads. Overland flow as well as other modes of land treatment are ideal for treating these wastes if sufficient land is available. Often, in forest or reservoir areas there is sufficient land available to allow for such a low rate of application that there is no runoff or percolation. Such systems are referred to as land containments and offer distinct advantages in many areas.

Future Needs

Overland flow has not been used or studied in detail as have slow and rapid infiltration systems. Demonstration systems using the present concepts of overland flow need to be constructed immediately in several areas of the United States. In addition, research into concept refinement and expansion needs to be pressed forward. If both of these tasks are carried out successfully, administrators, engineers, and scientists will come to recognize the proven value of overland flow treatment of wastewater and will recommend and adopt its use where appropriate.

Notes

1. S. Reed, "Wastewater Management by Disposal on the Land," *U.S. Army Cold Regions Research and Engineering Laboratory Special Report 171* (1972):183; R. H. Sullivan, M. M. Cohn, and S. S. Baxter, *Survey of Facilities Using Land Application of Wastewater*, EPA 430/9-73-006 (Washington: U.S. Government Printing Office, 1973), p. 377.
2. Sullivan, Cohn, and Baxter, *Survey of Facilities;* W. E. Sopper and L. T. Kardos, eds., *Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland* (University Park, Pa.: Pennsylvania State University Press, 1973). See also Chapter 31.
3. Sopper and Kardos, *Recycling Treated Municipal Wastewater.*
4. H. Bouwer, "Renovating Secondary Effluent by Groundwater Recharge with Infiltration Basins," *In Sopper and Kardos, Recycling Treated Municipal Wastewater*, pp. 164-75. See also Chapter 30.
5. C. A. Carlson, T. B. Delaney, Jr., and P. G. Hunt, "Overland Flow Treatment of Wastewater," *U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper* Y–74–3 (1974):63; L. C. Gilde et al., "A Spray Irrigation System for Treatment of Cannery Wastes," *J. Water Poll. Control Fed.* 43 (1971):2011-25; R. E. Hoeppel, P. G. Hunt, and T. B. Delaney, Jr., "Wastewater Treatment on Soils of Low Permeability." *U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper* Y–74–2 (1974):84; J. P. Law, R. E. Thomas, and L. H. Myers, "Nutrient Removal from Cannery Wastes by Spray Irrigation of Grassland," *FWPCA Report* No. 16080 (1969).
6. Bower, "Renovating Secondary Effluent"; Reed, "Wastewater Management."
7. Sopper and Kardos, *Recycling Treated Municipal Wastewater;* Bower, "Renovating Secondary Effluent."
8. Carlson, Delaney, and Hunt, "Overland Flow Treatment"; Hoeppel, Hunt, and Delaney, "Wastewater Treatment."
9. Reed, "Wastewater Management"; Sopper and Kardos, *Recycling Treated Municipal Wastewater.*
10. Carlson, Delaney, and Hunt, "Overland Flow Treatment"; Law, Thomas, and Myers, "Nutrient Removal"; R. E. Thomas, "Spray-Runoff to Treat Raw Domestic Wastewater" (Paper delivered at the International Conference on Land for Waste Management, Ottawa, Canada, 1–3 October, 1973).
11. Reed, "Wastewater Management"; Sopper and Kardos, *Recycling Treated Municipal Wastewater.*
12. Gilde, et al., "A Spray Irrigation System"; Law, Thomas, and Myers, "Nutrient Removal."
13. D. S. Mikkelsen and W. H. Patrick, Jr., "Plant Nutrient Behavior in Flooded Soil," In *Fertilizer Technology and Use* (Madison, Wis.: Soil Science Society of America, 1971), pp. 187-215; W. H. Patrick, Jr., R. D. Delaune, and R. M. Engler, "Soil Oxygen Content and Root Development of Cotton in Mississippi River Alluvial Soils," *Louisiana State University Agricultural Experiment Station Bulletin* 673 (1973); F. M. Ponnamperuma, ed., *The Mineral Nutrition of the Rice Plant* (Baltimore: The Johns Hopkins Press, 1965).
14. Carlson, Delaney, and Hunt, "Overland Flow Treatment."
15. *Ibid.*
16. Mikkelsen and Patrick, "Plant Nutrient Behavior"; Patrick, Delaune, and Engler, "Soil Oxygen Content"; Ponnamperuma, "The Mineral Nutrition"; R. A. Khalid and W. H. Patrick, Jr., "Phosphate Release and Absorption by Soils and Sediment," *Science* 186 (1974):53-55.
17. Khalid and Patrick, "Phosphate Release."
18. R. E. Thomas (EPA, Ada, Oklahoma), personal communication.
19. Carlson, Delaney, and Hunt, "Overland Flow Treatment."
20. Hoeppel, Delaney, and Hunt, "Wastewater Treatment"; Mikkelsen and Patrick, "Plant Nutrient Behavior"; Ponnamperuma, "The Mineral Nutrition."