Waste Treatment and Recycling

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Introduction

Land treatment is the practice of applying waste to a vegetation–soil complex with the intention of further treatment or renovation. Land treatment is based on well-documented scientific concepts which have been used successfully for wastewater (i.e. liquid sewage effluent) treatment at thousands of sites throughout the world. Properly designed and managed, land treatment systems can enhance productivity of forest ecosystems and, at the same time, protect the quality of surface and groundwaters. Of the various methods of wastewater land treatment, spray irrigation (also referred to as slow rate), achieves the highest degree of renovation and beneficial reuse of nutrients and water. The US *EPA Process Design Manual – Land Treatment of Municipal Wastewater*, published in 1981, describes land treatment by spray irrigation as: the application of wastewater to a vegetated land surface with the applied wastewater being treated as it flows through the plant–soil matrix. A portion of the flow percolates to the ground water and some is used by the vegetation. Treated wastewater produced by municipalities must be disposed of and one way of providing further treatment and reaping some benefits is to apply the wastewater to land, of which forest land is often the most suitable from an environmental and public acceptance viewpoint.

Assimilative Capacity of Forests for Wastewater Renovation

Wastewater is applied to a land treatment system at a rate designed to optimize the renovative capacity of the soil–plant complex and to maximize the utilization of the available nutrients in the wastewater. Renovation of the wastewater is accomplished through degradation by microorganisms, chemical precipitation, ion exchange, biological transformation, and biological absorption through the soil and vegetative cover complex. Utilization of a vegetative cover is an integral part of the land treatment system and complements the soil microbiological and physicochemical systems. Vegetation is one of the most essential elements of the land treatment concept and provides for the maximum renovation capacity and durability of the system.

Wastewater irrigation in a properly designed and operated land treatment system is such that all the applied wastewater will enter the soil and no overland flow will occur. In this respect, forested sites are often better suited for land treatment than agricultural sites because undisturbed forest soils often have infiltration and percolation rates far in excess of normal hydraulic loading rates. Once in the soil, wastewater is renovated relatively quickly by the various chemical, physical, and biological processes. Chemical constituents of the wastewater such as dissolved salts, metals, phosphorus (P), and nitrogen (N) are considerably reduced in concentration. Organic compounds are usually not found in domestic wastewaters or are only present in small amounts and have not been found to be a limiting factor in the functioning of a land treatment system. Organic compounds are readily absorbed to the organic surfaces of the soil system and thus have limited mobility through the soil profile. Pathogens and viruses in wastewater are filtered out in the upper soil profile. Survival time for most microorganisms following land treatment is typically very short. Viability depends upon a variety of soil and climatic conditions including temperature, soil moisture, and pH. Most bacterial and viral pathogens will die off to negligible numbers within 2–3 months following application. Research has shown that in a properly designed and managed system these organisms remain in the surface soils for the duration of their survival period and do not leach through the soil profile.

The assimilative capacity of a land treatment site is the amount of wastewater, on a constituent by constituent basis, that can be optimally applied to the land. The basic environmental constraint of nondegradation is used to develop the assimilative capacity for each constituent. The nondegradation constraint is stated: each constituent is applied at a rate over a time period (mass of chemical species per unit area per unit time, i.e., $kg\,ha^{-1}\,year^{-1}$) that the land and water resources are not irreversibly converted to an unproductive condition or environmentally degraded. Use of such a strong constraint parallels environmental regulatory intent and provides for long-term and successful wastewater irrigation.

Wastewater Constituents and System Design

Land-applied wastewater constituents can be divided into three primary groups:

1. Those compounds that degrade or require plant uptake for assimilation in the plant–soil system (e.g., N, oil, organics).
2. Those mobile and nondegradative compounds that must be assimilated over land areas such that groundwater is not altered to a degree that would require further treatment to meet drinking water or other applicable standards (e.g., anionic species such as sulfate, chloride, boron, and fluoride).
3. Those compounds that are relatively immobile and nondegradative, and thus are permitted to accumulate in the soil to predetermined acceptable levels (e.g., trace metals). For calculation purposes, an operations period must be specified over which the total mass loading of constituents will be distributed.

Development of design criteria for a land irrigation system involves identification of the significant constituents of the waste stream, classification of each constituent into one of the above categories, and evaluation of the assimilative pathway(s) utilized for that constituent. The three principal components of assimilative pathways are the soil, vegetation, and groundwater. The land-limiting constituent (LLC), the waste constituent requiring the greatest land area, is determined from the assimilative capacities and wastewater characteristics. The LLC is determined by dividing the total mass of each constituent to be applied on an annual basis (kg year^{-1}) by the site assimilative capacity (kg ha^{-1} year^{-1}). Typically for municipal wastewater the LLC is either hydraulic loading or nitrogen.

The amount of wastewater irrigated is referred to as the hydraulic loading. Hydraulic loading must be balanced with vertical and lateral water movement in the soil, ground water movement, vegetation tolerances for soil wetness, and losses by evapotranspiration. Determination of hydraulic loading requires characterization of soil water movement to estimate the percolation rate, or rate of water movement through the hydraulically restrictive soil horizon (i.e., the first horizon encountered in the soil profile with a reduced permeability). This is accomplished by direct field testing of soil hydraulic conductivity. The irrigation system design and management is specified such that no overland flow of applied wastewater will occur, that is, all applied wastewater must infiltrate, or enter, the soil surface. Thus, the only pathways by which applied water may leave the site are evapotranspiration and percolation through the soil profile. Application of these principles in design and operation meets regulatory compliance for water quality and best management practices. Infiltrated wastewater that percolates through the soil profile (sometimes referred to as interflow) may emerge downslope in stream channels or seepage areas at the base of slopes as return flow, or percolate directly to groundwater and eventually to a stream channel or a regional groundwater aquifer. Residence time of water in the soil must be sufficient for all the physical, chemical, and biological renovation processes to occur and is controlled through timing of wastewater application and application rates. Typically, application rates are low (less than 6 mm h^{-1}) to achieve long residence times and slow rates of subsurface flow and, consequently slow return flow and/or percolation to groundwater. It is this long residence time and the high renovation capacity of the soil and vegetation complex which yields highly renovated subsurface flow (interflow) that emerges as return flow or percolates to groundwater. For most wastewater constituents, travel through only a few inches of soil and forest floor achieves 90–100% of the potential renovation. In humid regions, where rainfall exceeds evapotranspiration by 25–30%, strong development of subsurface flow and return flow in forested landscapes is a common occurrence, particularly during the wetter seasons of the year. Wastewater irrigation accentuates these processes such that they occur throughout the year.

The N cycle in a forest ecosystem is complex, dynamic, and varies with species, growth rates, soil morphology and fertility, climate, and other environmental factors. To determine the N assimilative capacity, a N budget is constructed to balance inputs with losses. All the N in municipal wastewater is typically plant available because the organic N will be readily mineralized to ammonia. Ammonia-nitrogen is not highly mobile, is retained within the soil complex, and is taken up by plants. Nitrate-nitrogen, on the other hand, is easily leached from the root zone and its assimilation is controlled through plant uptake and denitrification. Control of nitrate leaching is critical to maintain nitrate in groundwater at the drinking water standard (typically 10 mg l^{-1} nitrate-nitrogen). Nitrogen may be stored on the site as organic-nitrogen in bacterial cells as well as in living and dead plant material. It may also be stored as ammonia-nitrogen adsorbed on soil cation exchange surfaces. Ammonia-nitrogen may be volatilized to the atmosphere, transformed to nitrate-nitrogen by nitrifying bacteria, and/or taken up by vegetation. Nitrate-nitrogen may be taken up by vegetation, transformed to nitrogen gas by denitrifying bacteria, or leached to the groundwater. All of the N assimilative pathways occur simultaneously in natural systems. Nitrogen is removed primarily by crop uptake, which varies with the type of crop grown and the crop yield.

To remove the N effectively, the forest crop must be harvested periodically. Denitrification can also be significant, even if the soil is in an aerobic condition most of the time. Other N removal mechanisms include ammonia volatilization and storage in the soil.

Thus, N management in a land treatment system is achieved through management of vegetation and denitrification. Vegetation must be harvested and N removed in the biomass. Denitrification occurs naturally but can be enhanced by creating periodic soil saturation and providing available carbon. Irrigated wastewater and forest ecosystems have adequate supplies of organic carbon and management of hydraulic loading can create the requisite soil wetness. Management of denitrification is further enhanced in sloping sites because the infiltrated wastewater can move laterally through the soil profile maintaining the wet soils for the short periods required to drive the denitrification process.

Phosphorus added to the soil from wastewater undergoes a variety of biological and chemical reactions. The predominant phosphorus pool in the soil is in the inorganic form. That is, the P is physically part of the soil matrix. A much smaller pool of P is in the organic matter (organic phosphorus) and in a soluble form as part of the soil pore water. Soluble P is the only form that is available to the plant. Chemical fixation of P in the soil occurs under all soil pH ranges with the least occurring in the range of 5.8 to 6.8. The adsorption and precipitation processes at low soil pH are dependent on the amount of aluminum (Al), iron (Fe), and manganese (Mn) present. These elements are abundant in the highly weathered soils. Natural occurring P in geologic materials is also relatively low. Thus, acidic soil pH, abundant Al, Fe, and Mn, and low residual P levels in forest soils provide a high capacity for sequestration of P added from wastewater irrigation. A study of a forest wastewater irrigation site in north Georgia (southeastern USA) showed there was a residual P fixation capacity of over 100 years in the surface soils. The residual capacity of soils to chemically fix P is determined by laboratory determination on soil samples of adsorption and precipitation isotherms. Vegetation uptake and incorporation of organic P is minor compared to the capacity of the soil to fix and retain P. The residual forest floor (leaf litter and partially decomposed material) retains P also in a form that is largely unavailable to plant uptake or leaching. Phosphorus removal efficiencies are generally very high for spray irrigation systems and are more dependent on the soil properties than on the concentration of the P applied. Although P is held within the soil at different energy levels, little or no leaching occurs. This is demonstrated by groundwater concentrations beneath both natural and wastewater irrigation forested sites on the order of 0.01 to $0.1\,\mathrm{mg\,l^{-1}}$. The principal nonpoint source of P to streams is runoff of soil and organic particles with 'attached' P.

Organics applied in the wastewater are reduced substantially within the top 1.5–2.5 cm of soil. Filtration and adsorption are the initial steps in biological oxygen demand (BOD) removal, but biological oxidation is the ultimate treatment mechanism. Filtration is the major removal mechanism for suspended solids. Residues remaining after oxidation and the inert solids become part of the soil matrix.

Metals, much like P, are retained in the soil complex and are immobile. Metals in municipal wastewater are rarely found in concentrations that result in any one becoming a land-limiting constituent.

Impacts of Wastewater Treatment: Case Study of Clayton County, Georgia, USA

Irrigation of secondary treated wastewater to a 1000 ha and mixed pine (*Pinus taeda*) and hardwood (*Quercus, Carya, Liquidambar*) forest site began in 1983 and continues to the present with an average flow of $0.85\,\mathrm{m^3\,s^{-1}}$. Clayton County is located in the metropolitan Atlanta, Georgia area and has few heavy industry waste dischargers. Wastewater treatment by activated sludge occurs at two plants and the wastewater is combined and pumped 11 km to the land treatment site.

The site is within the headwaters of Pates Creek. The site is entirely forested and about 50 ha are harvested annually. Geologic structure is dominated by granitic gneiss with some fracturing and jointing. Groundwater occurs under water table conditions and most of the recoverable water is above the bedrock at depths of 3–25 m. Hydraulic conductivities of the saprolite overlying the bedrock are low, averaging $5 \times 10^{-4}\,\mathrm{cm\,s^{-1}}$. Dominant soils are typic hapludults with A horizon textures ranging from fine sandy loam to sandy clay loam. The B horizon is argillic with sandy clay to clay textures. Depth of the A is shallow due to past erosion history and rarely exceeds 15 cm. B horizon hydraulic conductivities average $9 \times 10^{-4}\,\mathrm{cm\,s^{-1}}$. Soils are classified as well drained except in alluvium along streams.

Wastewater loading is limited by nitrogen and water assimilative capacities of the site. Wastewater irrigation is limited to 6.3 cm water week^{-1} which has resulted in maximum N applications of about $395\,\mathrm{kg\,ha^{-1}\,year^{-1}}$. The irrigation system is solid-set buried PVC and ductile iron with galvanized steel risers and brass and plastic sprinklers. There are over 18 000 sprinklers and the pressure at the nozzles is about 345 kPa for an application rate of $5\,mm\,h^{-1}$. Storage equivalent to 12 days' flow is provided for flow equalization and inclement weather.

An intensive environmental monitoring program has been implemented at the Clayton County land treatment site that includes groundwater, surface water, soil, and vegetation. In addition numerous research projects have been undertaken that include changes in streamflow from the first order basins, changes in streamflow and water budget for the entire irrigated watershed, nitrogen gas evolution from the soil, earthworm populations, and soil hydraulic properties. Twenty-two groundwater wells as well as several private water supply wells in and around the site have been monitored. In the early years of operation, the wells were monitored monthly and as the project progressed and no significant impacts to water quality were demonstrated, the regulatory permit was modified to a mix of quarterly, semi-annual, and annual monitoring for different wells. The most frequent monitoring is conducted at wells located down gradient from the irrigation site. Surface water as it discharges from the site is monitored at Clayton County's water supply intake about 10 km downstream.

Groundwater quality has been monitored since 1979, over 4 years prior to commencement of wastewater irrigation. Initially, many inorganic parameters were monitored, including nitrate-nitrogen, phosphate, chloride, specific conductivity, a number of metals, and coliforms. Later, analysis of metal and coliforms was discontinued except for a few interior and down gradient wells on an annual basis.

Wells have been grouped by permit conditions as up gradient, interior, and down gradient. Considering the most mobile constituents monitored (chloride and nitrate-nitrogen) and specific conductivity, there have been increasing trends to what appears to be a plateau concentration for chloride and specific conductivity and an initial slight increase in nitrate-nitrogen with no long-term increasing trend since irrigation began in 1983. Chloride and nitrite-nitrogen concentrations and specific conductivity in the background (up gradient) wells average about $10\,mg\,l^{-1}$, $0.1\,mg\,l^{-1}$, and $80\,uSc\,m^{-1}$, respectively, and have remained somewhat constant since monitoring began in 1979. In contrast, chloride concentrations and specific conductivity in the down gradient wells (immediately outside the irrigation area) have steadily increased from 10 to $20\,mg\,l^{-1}$ and from 80 to $150\,uSc\,m^{-1}$, respectively. This represents a doubling in 12 years of irrigation. Both parameters, however, are well below the maximum contaminant level (MCL) for drinking water. Nitrate-nitrogen concentrations, on the other hand, in the down gradient well have increased to an average of $0.5\,mg\,l^{-1}$. Most of the increase in nitrate-nitrogen concentration came within 10 years of commencement of irrigation and has remained at the increased level since (**Figure 1**). Nitrate-nitrogen increases in the down gradient wells are not significantly different from preirrigation levels.

Monitoring also indicates that irrigated wastewater is percolating to the groundwater as evidenced by increases in chloride and specific conductivity. The interpretation drawn from the steadily increasing chloride and specific conductivity and no increasing trend in nitrate-nitrogen is that plant uptake and denitrification, which occurs at higher rates in irrigated areas than in nonirrigated forests (**Figure 2**), are occurring to the extent that little nitrate is reaching the groundwater.

About 8% of Pates Creek watershed above the drinking water supply reservoir is irrigated with wastewater. Water quality monitoring has been

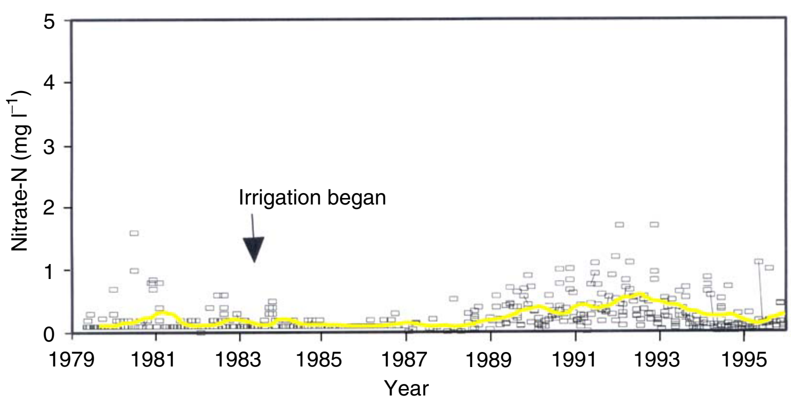

Figure 1 Trend of nitrate-nitrogen in the down gradient monitoring wells. The line is a moving mean and the symbols represent readings from five wells.

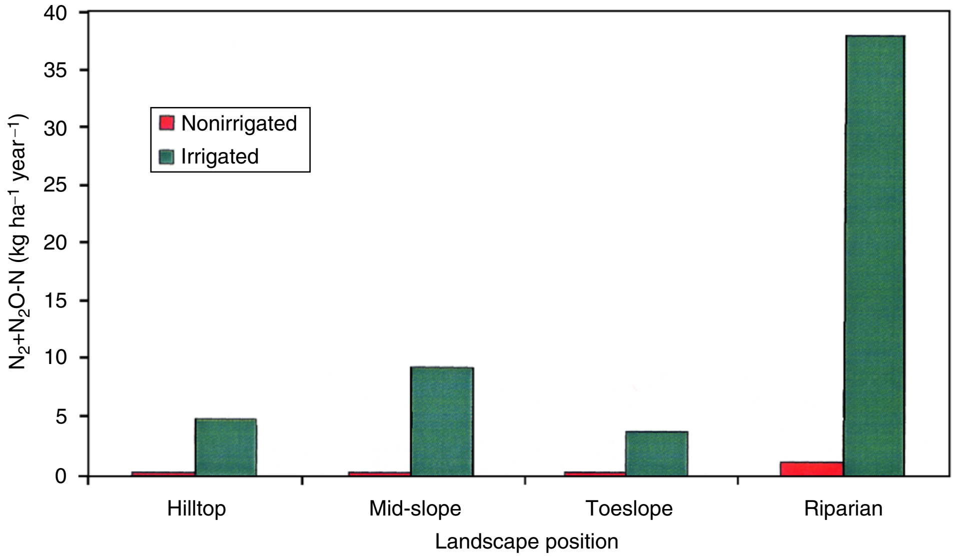

Figure 2 Annual denitrification in wastewater irrigated forests and adjacent nonirrigated forests in the Piedmont of the southeastern USA.

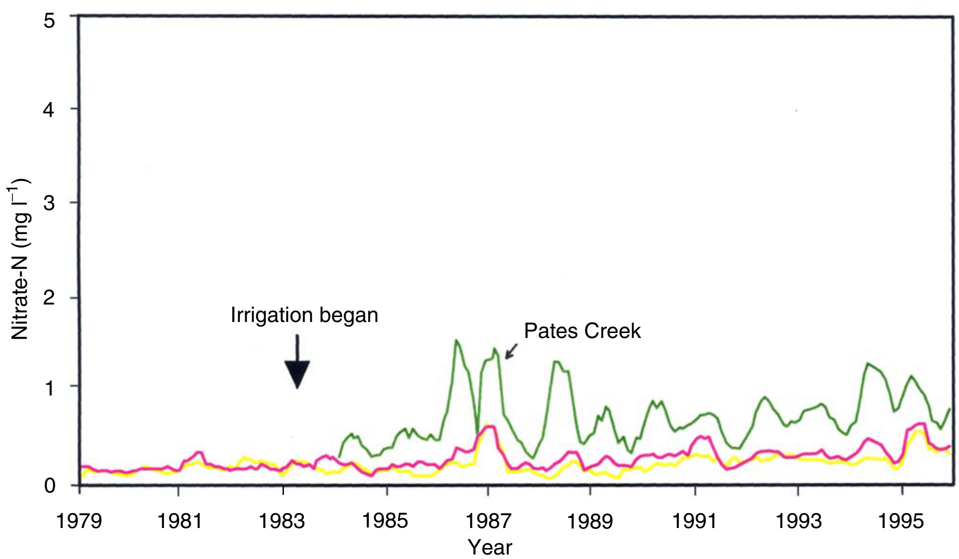

Figure 3 Trend of nitrate-nitrogen in Pates Creek draining the land treatment system compared to two nearby streams. Pates Creek flows directly to the drinking water reservoir.

conducted at the head of the reservoir and at two tributary streams that do not receive wastewater irrigation but are experiencing expanding urbanization. Pates Creek exhibits similar water quality changes that have occurred in the groundwater. Although there is greater variation in streamwater quality than groundwater quality, specific conductivity in Pates Creek has remained steady at an average of about 100 uSc m^{-1}. Nitrate-nitrogen has also remained steady at about 1.0–1.5 mg l^{-1} (**Figure 3**) but chloride has steadily increased from an average of about 10–20 mg l^{-1}. These later results are in direct correspondence with groundwater quality. Reeves Creek and Rum Creek, the two nonirrigated background monitored streams, have similar specific conductivity and nitrate-nitrogen concentrations as Pates Creek and chloride concentrations are similar to and unchanged from the initial preirrigation concentrations in Pates Creek.

Infiltration rates have remained high on the site due, in part, to the activity of earthworms, which occur in much higher numbers within irrigated forests than in nonirrigated forests. Tree growth and nutrient accumulation has been periodically assessed at Clayton County. In general, trees irrigated with wastewater have higher foliage nutrient concentrations and exhibit more rapid growth than trees grown on adjacent sites without irrigation.

Summary

1. The concept of land treatment of wastewater has a sound scientific and experience foundation which has proven that land can be used to renovate wastewater in a environmentally acceptable manner and that such land is not irreversibly withdrawn from any present or future societal use.
2. No human or animal health problems have been reported and studies have concluded that properly designed and operated wastewater irrigation systems are likely to pose less environmental health problems than most other wastewater treatment technologies.
3. Forests can be successfully used as the principal vegetative cover in a land treatment system. It has in fact a number of advantages over agronomic crops including greater flexibility to operate around climatic conditions, fewer interruptions to the irrigation schedule, and can be operated year-round.
4. The design of a forest system must be based on potential performance of the site to meet water quality performance criteria objectives including hydraulic capacity as well as nitrogen assimilative capacity. Both of these factors normally influence the total performance of the land treatment system.
5. Successful operation of the land treatment system is evaluated on the basis of performance standards established by water quality objectives.

See also: **Hydrology**: Impacts of Forest Conversion on Streamflow. **Silviculture**: Forest Rehabilitation. **Site-Specific Silviculture**: Silviculture in Polluted Areas. **Soil Development and Properties**: Water Storage and Movement. **Tree Breeding, Practices**: Nitrogen-fixing Tree Improvement and Culture.

Further Reading

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Water Storage and Movement

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Introduction

Water storage and movement in forest soils is a key regulator for a variety of hydrological, physiological, and biogeochemical processes in a forest. The climate and geology controls on soils vary around the world; these can range from conditions of colluvial infilling of steep unstable hollows in and around the Pacific Rim, to till soils that develop on recently glaciated sites in Scandinavia, eastern Canada, and Russia, and