

SECTION II RENOVATION OF WASTEWATER IN SUBSURFACE SOILS

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SECTION II RENOVATION OF WASTEWATER IN SUBSURFACE SOILS

A. Introduction

This section discusses: 1.) pollutants usually present in domestic wastewater that are of most concern with respect to adverse effects on human health and the environment; 2.) properties of soils that effect wastewater renovation; and 3.) the ability of the subsurface soil environment to remove or attenuate pollutants in the pretreated wastewater discharged to a subsurface wastewater absorption system (SWAS). More specific information on each of the topics discussed herein is given in some of the following sections of this document.

Pollutants contained in domestic wastewater include suspended and dissolved biodegradable natural organic chemicals, a wide range of synthetic organic chemicals (usually in the dissolved form and varying in their susceptibility to biodegradation), inorganic chemicals (including heavy metals) and pathogenic microorganisms that can be harmful to humans and/or the environment. The wide range in the types and concentrations of such pollutants speaks to the need to exercise caution when selecting pollutant concentration values for designing on-site wastewater renovation systems (OWRS).

While domestic wastewater receives some pretreatment, either in a septic tank and/or other pretreatment facilities, prior to discharge to the subsurface via a SWAS, the effluent from these pretreatment facilities still contains pollutants that can adversely effect human health or the environment. It has been amply demonstrated by numerous investigators, in the U.S. and elsewhere, that most soils have substantial but finite capacities to accomplish the renovation of pretreated domestic wastewater by providing an environment that causes removal or attenuation of chemical pollutants and the death or inactivation of pathogens.

With respect to the soil's capacity to accept and renovate a discharge of pretreated wastewater, two separate capacity factors must be considered. The first factor is the soil's hydraulic capacity to accept, contain and transport the pretreated wastewater in such a manner that renovation will occur before the pretreated wastewater reaches a point of public health or environmental concern. This capacity depends upon the soil's hydraulic conductivity (a measure of how easily water flows through the soil), the driving force (hydraulic gradient or pressure head) available for inducing flow through the soil, and the cross-sectional area of the soil through which the pretreated wastewater must flow.

The second factor is the soil's renovative capacity. For a particular soil, this is a volumetric capacity. It depends upon volume of soil through which the pretreated wastewater flows, and the renovative capacity per unit volume of soil for each pollutant.

It has been found that significant renovation is achieved as the wastewater flows through a biomat that forms at the infiltrative surface of the SWAS and then into an unsaturated, aerobic soil zone between the bottom of the SWAS and the water table. To obtain this renovation, there must be an adequate depth of unsaturated soil, and the pretreated wastewater must be applied in such a manner and at such a rate as to not overwhelm the renovative capacity of the unsaturated soils.

Additional renovation of the wastewater can and often does continue to take place after the pretreated wastewater has percolated through the unsaturated zone and reached the ground water. This renovation is a function of the renovative capacity of the soil in the saturated (ground water) zone and the time it takes for the commingled percolate and ground water to reach a point of concern, such as a drinking water supply well, property line or surface water body. This travel time is generally a function of the horizontal separating distance between the SWAS and the closest point of concern and the velocity of a pollutant as it travels with or through the ground water. The horizontal separating distance is important in that it provides time for the pollutants remaining in the commingled waters to be exposed to environmental conditions in the saturated soils that results in their additional decay or attenuation.

B. Soil Features and Wastewater Renovation

In the following discussion on soil features as they effect wastewater renovation, the terminology used is that of soil scientists, rather than that normally used in geotechnical engineering. It is the terminology used by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) in their soil survey reports and other soils publications. There are several NRCS references listed in the bibliography at the end of this section that provide a great deal of information on soils. The reader is urged to refer to them, or references of similar content, to gain a fuller understanding of soil features that are only discussed in a very rudimentary manner herein.

The NRCS has published a soil survey for each of the eight counties in Connecticut. However, the new digital “Soil Survey of the State of Connecticut, dated July 15, 2005”, is the official soil survey for the state. The digital survey can be found on the website: <http://www.ct.nrcs.usda.gov>.

The soil maps included in the soil survey show the kinds of soils in an area and their location, distribution and extent. These maps provide useful information for site screening and planning purposes, but are inadequate for obtaining the detailed soils information required for design of a SWAS. The boundaries of the soil mapping units are not a perfect representation of the soil patterns on the ground. This is because soils grade from one to another and are not always present in bodies large enough to delineate at the map scale used for the maps included in the various soil surveys of Connecticut counties.

For example, the minimum size delineation at a map scale of 1:15840 (typical of the original county soil maps) is 2.5 acres. The new soils maps, to be published at a scale of 1:12,000, will have a minimum size delineation of 1.43 acres (Sautter - 1990). Soil differences often occur within short distances. Within most mapping units are small areas of soils (inclusions) that differ significantly from the named soils. They are typically too small to be delineated separately (NRCS-1991). Thus, while a soil survey report is highly useful in gaining broad understanding of landscapes, having such a report in hand does not remove the need for onsite investigation in determining suitability of soils for SWAS (Brown, R.B.-1992)¹.

The soils in Connecticut were formed from parent materials deposited during at least two separate occasions by glaciers that covered the entire region with ice sheets ranging up to thousands of feet in depth. These soils have a wide range of complexities in their characteristics. They have been classified into 94 major soil series (the basic units of soil classification) consisting of soils that are essentially alike in all major profile characteristics. Each of these soil series has a definite relationship to the landscape, local geology, and parent materials (Sautter - 1990). The local geological and hydrologic conditions associated with these soils greatly modify the capacity of the soils to accept and renovate domestic wastewater. This association is complex and provides an infinite spectrum of soil capabilities for accepting and renovating wastewater and eliminates the use of generalizations for the use of soil as a medium for wastewater renovation (Miller and Wolfe-1982, Reneau, et al.-1996).

The soil series, consisting of a characteristic profile with a unique arrangement of horizons, occur in a variety of landscape positions. Each soil profile depicted is a vertical cross section of the undisturbed soil showing the characteristic soil horizons (horizontal layers), that have formed as a result of the combined effects of parent material, topography, climate, biological activity, and time.

The soil horizons consist of more or less distinct layers of soil running approximately parallel to the soil surface and they have distinct characteristics produced by pedogenic (soil-forming) processes. They are normally designated alphabetically, but not necessarily in alphabetic order, proceeding vertically through the soil profile from the soil surface downward. An upper case letter represents the major horizons; numbers or lower case letters that follow represent subdivisions of the major horizons. The thickness of each horizon can vary considerably in relatively short horizontal distances, and not all horizon designations may be present at any one location.

¹ Other sources of information on subsurface conditions can be found in the various publications available from the CT DEP Natural Resources Center. These include such publications as the State Geological and Natural History Surveys of Connecticut (bedrock geology, surficial geology), the U.S. Geological Survey Water Resources Inventories of Connecticut and Surficial Geology Quadrangle Maps, and other similar publications covering various locales in the State.

The master horizons include:

O-horizon	An organic layer of fresh and decaying plant residue (litter and humus) at the surface of a mineral soil.
A-horizon	The mineral soil at or near the surface in which an accumulation of decayed organic matter (humus) is mixed with the mineral material, which predominates.
E-horizon	Consists of mineral soil characterized by the loss of iron, aluminum, calcium, clay or organic matter to the underlying B-horizon due to leaching.
B-horizon	The mineral soil below an A-horizon or E-horizon. It is in part a transitional layer from the overlying soil horizons to the C-horizon. It contains accumulations of clay and metals (e.g. iron, aluminum, calcium) and humus.
C-horizon	The mineral layer, excluding bedrock, which is little effected by soil forming processes and does not have the properties typical of the overlying horizons.
R-horizon	Bedrock.

These horizons can also be grouped into surface soils, subsurface soil, subsoil, and substratum. A very basic description of these groupings, taken from R.B. Brown (1992), is given below:

- Surface Soil. The surface soil, or “topsoil”, is enriched in organic matter -- and usually darkened somewhat as a result -- from decomposing organisms.
- Subsurface soil. The subsurface horizon, if present, is a leached zone, beneath the surface soil, from which mobile soil constituents (clay particles, organic matter, iron and aluminum oxides, carbonates, and/or other constituents) have been removed in solution or suspension by downward-percolating rainwater and/or by a fluctuating water table.
- Subsoil. Underlying the surface soil and/or subsurface soil may be “subsoil”. The subsoil, where present, is a zone that has been influenced in some significant manner by soil-forming processes. These processes may be subtle, consisting of simple alteration of chemicals and minerals, or very distinct, consisting not only of alteration but enrichment of subsoil horizons by materials that have been leached from the overlying topsoil and subsurface soil and deposited in the subsoil. Where such enrichment has occurred, a relatively clayey horizon, a horizon enriched with organic materials and iron and aluminum oxides, or other horizons marked by some sort of accumulation may result.

- Substratum. Beneath the zone of soil formation is the “substratum”, which is non-soil material, ranging from bedrock to unconsolidated sediment. Substrata are largely unaffected by soil-forming processes other than deep weathering.” This is equivalent to the master C-horizon.

In addition to the soil-forming factors of alteration, leaching, and enrichment, the stratification of soil or soil parent materials can have enormous impact on the behavior of water in soils. Stratification is the result of deposition of relatively fine-textured layers over and/or under coarser-textured layers. Behavior of water, including septic tank effluent, is a function of such layering, of the permeability of the various soil horizons, position in the landscape, weather and other factors (R.B. Brown -ibid.).

Inspection of the soil survey reports for the Connecticut counties reveals that the B-horizon rarely extends more than 2.5 ft below the A-horizon. Below this depth lies the C-horizon, which is usually lacking in the soil characteristics discussed below which contribute the most to wastewater renovation. This indicates that the portion of an SWAS located below the B-horizon will not make use of the most effective characteristics of the soil profile.

Those soil features which effect the removal or attenuation of pollutants remaining in the percolate discharged to the soil beneath a SWAS (e.g. natural organics, suspended solids, nitrates, phosphates, human pathogens and toxic organic chemicals), include:

- texture and structure,
- silt, clay, organic and reactive mineral content,
- microbial population,
- soil gas oxygen content,
- cation exchange capacity,
- pH,
- alkalinity,
- temperature; and
- moisture content.

Soil texture refers to the visual or tactile surface characteristics of soil, and to the distribution, on a percent by weight basis, of sand, silt and clay. Soil structure is the arrangement or grouping of individual soil particles into aggregates or clusters (Peds). The principal forms of soil structure are blocky (angular or sub-angular), columnar (prisms with rounded tops), granular, platy (laminated) and prismatic (vertical axis of aggregates longer than horizontal). Structure-less soils are either single grained (each grain by itself) or massive (the particles adhering without any regular cleavage, as in many dense till soils).

Texture and structure are important factors governing the movement of water, pollutants, and microbial populations in porous media. Clay particles are particularly dominant in determining the physical and chemical properties of soils. For example, clays, which are often composed of aluminum silicates, add both surface area and charge to a soil. The surface area of a clay particle can be five orders of magnitude larger than the surface area of a 2 mm sand particle (Maier and Pepper - 2000). These characteristics

(surface area and electrical charge) of clays play an important part in the sorption of pollutants. Structure is important in that a few large macropores (voids left by decayed roots, cracks, animal and worm burrows, etc.) in the soil can have a very large influence on the soil's ability to transmit wastewater.

Under saturated soil conditions, wastewater fills all the soil pores; however under unsaturated conditions it flows predominately through the small pores or is retained as a film around soil particles. When all soil pores are filled with wastewater, the macropores in structured soils (and the larger pores in coarse-grained unstructured soils) transmit most of the wastewater at rapid rates and do not allow the pollutants to come into close contact with the soil particles. Wastewater flowing through the small pores in unsaturated soils travels at a slower rate, and through a more tortuous path, giving more time for close contact of the pollutants with the soil particles. Such close contact is of paramount importance for sorption of pollutants onto the soil particles, which is in many cases the necessary first phase in the attenuation or removal of pollutants from wastewater.

Two other soil characteristics are important to the design and operation of a SWAS. These are hydraulic conductivity (a measure of how easily water flows through soil), and porosity (the ratio of the volume of pores in a soil to the bulk volume of the soil). These characteristics are a function of a soil's texture, structure and bulk density. Hydraulic conductivity is also a function of the temperature of the liquid, although this is typically ignored as being insignificant in design of a SWAS, and the soil moisture content. (Note: In the past, the term "permeability" was often used in some texts and technical papers, rather than "hydraulic conductivity", to define the soil characteristic used to determine the hydraulic capacity of the soil. However, "permeability" has been replaced by "hydraulic conductivity" in the current literature, since these terms refer to somewhat different soil characteristics, and it is the hydraulic conductivity of a soil that is of interest in designing a SWAS. Thus, unless otherwise stated, wherever the term "permeability" is encountered in this document, it shall be taken to mean "hydraulic conductivity".)

Dilution of pollutants, such as nitrates and toxic organic chemicals in the SWAS percolate, by precipitation infiltrating to the ground water beneath and downgradient of a SWAS, and by dispersion in the ground water, has been found to be generally much less than assumed in previous decades. Therefore, consideration needs to be given to optimize the conditions that permit the unsaturated, aerobic soil located above the water table to remove or attenuate pollutants. Understanding and identifying those soil features that are vital to the soil's ability to renovate wastewater is required prior to designing an SWAS in order to make efficient use of the renovative capacity of the soil. Only then can informed decisions be made with respect to SWAS design parameters such as system siting, layout, hydraulic and pollutant loading rates, etc.

C. Pollutant Removal Processes

Pollutants are removed from wastewater in and below a SWAS by several processes, including:

- Physical processes, such as filtration of suspended solids and some microorganisms;
- Biodegradation processes that transform organic and inorganic pollutants into harmless or less harmful substances;
- Sorption (absorption, adsorption, chemisorption and chemical precipitation) processes that remove chemicals and microorganisms from the wastewater; and,
- Biological and physiochemical processes that result in the death or decay of pathogenic microorganisms.

When wastewater receiving pretreatment in a septic tank is discharged to a SWAS, a slimy biomat begins to form at the infiltrative surface of the soil, and eventually reaches a thickness of one or more centimeters, depending upon the amount of organic matter and suspended solids in the wastewater. This biomat consists of an accumulation of suspended solids filtered from the wastewater, indigenous soil microorganisms (both their active cells and cell remnants), the slimes (e.g. polysaccharides) produced by these microorganisms and various minerals. The biomat acts as a filter and as a medium for biochemical degradation, absorption and adsorption of pollutants; it plays an important part in the pollutant removal process, as a significant amount of pollutant removal occurs as the wastewater contacts and passes through the biomat.

The biomat also serves to restrict the rate of flow of wastewater through the adjacent soils. This results in the wastewater flowing through the smaller soil pores, bringing the wastewater into close contact with the soil particles while allowing the larger soil pores to remain open to the diffusion of atmospheric oxygen into the subsurface soils. The slower flow rate through the smaller pores results in increased contact time between the pollutants and the soil particles. It is the increased contact time, the close contact of the wastewater with the soil particles, and the existence of an aerobic environment that results in the efficient removal or attenuation of the pollutants.

Various types and species of microorganisms exist on and within the biomat. Of major importance are the heterotrophic aerobic, anaerobic and facultative bacteria, which require organic carbon as a food source, and the autotrophic bacteria, which obtain their carbon from inorganic compounds (e.g. carbon dioxide). All bacteria require water and a food source to exist. Aerobic bacteria also require the presence of free dissolved oxygen for their metabolic processes, whereas anaerobic bacteria obtain their oxygen by breaking down chemical compounds, and cannot function in an aerobic environment. Facultative bacteria have the unique ability to function in either an aerobic or anaerobic environment, although they function much more efficiently under aerobic conditions. Autotrophic bacteria are strict aerobes.

It is important to note that the removal or attenuation of most pollutants in domestic wastewater is best accomplished in an aerobic soil environment.

As the pretreated wastewater percolates through the biomat and reaches an aerobic, unsaturated soil zone beneath the SWAS, biochemical degradation continues to occur, and in addition, certain pollutants become sorbed to the soil particles. This sorption process can be irreversible or reversible, depending upon the nature of the attractive forces between the pollutants and the soil particles, the pH of the soil solution and the soil moisture content. Pathogens may be adsorbed for a sufficient time to allow their degradation by indigenous antagonistic microorganisms, or by their natural death or decay (inactivation) processes. Heavy metals may also be sorbed and immobilized. Soils with the highest percentage of clay and iron oxides, and greatest cation exchange capacity are most effective in immobilizing heavy metals (McHugh - 1990). However, all soils have a finite sorption capacity and, if that capacity is exceeded, pollutants in percolating wastewater can enter and travel with the ground water.

It is also possible that after reaching the ground water, pollutants may continue to be filtered, sorbed or biochemically degraded. However, in the latter case the ground water is generally anoxic or anaerobic, and thus the biochemical processes are much slower than the aerobic processes that take place in the unsaturated zone. In most cases the saturated soil is limited or lacking in organic material and this also hinders the microbes that require such material for their metabolic processes. Where there is insufficient travel time between the point of entry of the pollutants into the ground water and a point of concern, the pollutants may not be removed before they reach the point of concern.

D. Suspended Solids

Domestic wastewater contains both organic and inorganic suspended solids (TSS, or total suspended solids). These suspended solids, if not largely removed in the septic tank, can clog the pore spaces between soil grains at the soil interface with the infiltration system and the biomat that forms at that interface.

While some of the organic suspended solids may be biochemically degraded in the biomat, and thus cause a biochemical oxygen demand, some are highly resistant (refractory TSS) and may take a long time to degrade. It is therefore important to minimize the carryover of TSS from the septic tank or other pretreatment facilities.

E. Organic Chemicals

When wastewater containing biodegradable organic chemicals is discharged to the subsurface, these organics are used as a source of food and energy in the metabolic processes of various microorganisms indigenous to the soil and ground water. As a result, these organics are largely removed from wastewater provided the environmental conditions in the subsurface are suitable for the microorganisms. Many of these indigenous microorganisms are aerobic, requiring free (molecular) oxygen for their metabolic processes.

The principal sources of free oxygen are the gaseous molecular oxygen that has diffused from the atmosphere into the unsaturated pores of the soil and the free molecular oxygen that is dissolved in the ground water. If sufficient free molecular oxygen is available, the aerobic microorganisms will rapidly degrade the organic chemicals to carbon dioxide, water and new microbial cellular material.

However, if an excess amount of organic chemicals is discharged to the subsurface, the oxygen present will be depleted as the numbers of aerobic microorganisms increase in an attempt to utilize this “food”, resulting in anoxic (very low free oxygen concentrations) or anaerobic conditions (no free oxygen present) prevailing. When these conditions occur, anaerobic or facultative microorganisms that are able to exist and function when free molecular oxygen is absent or present in very low concentrations will utilize chemically bound oxygen in their metabolic processes to degrade the organic chemicals.

However, under anaerobic conditions, the degradation of the biodegradable organic chemicals is slower and less efficient, and the degradation by-products can cause undesirable taste, odor and color in the water, making it unpalatable. Therefore, it is critical that aerobic conditions are maintained in the subsurface into which wastewater is introduced.

Many synthetic organic chemicals, both volatile and non-volatile, have been found to be toxic to humans and other life forms in low concentrations in water. Synthetic organic chemicals are found in numerous household products, including cleaning agents, solvents, “septic system cleaners” pesticides, pharmaceuticals and personal care products (drugs, including antibiotics; food supplements, fragrances, sunscreen agents, etc.).

Some investigators have indicated that where the concentrations of these chemicals in wastewater are low, many are substantially degraded by microbial action in the biomat and unsaturated soils before they reach the ground water (Bicki and Lang - 1991; Robertson, et al. - 1991; Sherman and Anderson - 1991; Siegrist, et al. - 2000). However, other investigators have determined that in some cases, synthetic organic chemicals can and do reach the ground water. Samples of untreated ground water from 1,926 rural, self-supplied domestic wells were tested for volatile organic compounds (VOCs) during the period 1986-1999. Water samples were collected at the wellhead prior to treatment or storage. In most samples, analyses were conducted for 55 target VOCs, and occurrence and status information generally was computed at an assessment level of 0.2 µg/L. The seven most frequently detected VOCs have many uses in a variety of household products and have been found in septic tank systems. For example, tetrachloroethene is predominantly used as a solvent, but also is used in products such as household cleaners and products used for personal hygiene. At least one VOC was detected in 12 percent of samples at the assessment level, with detection of at least one VOC found in samples collected from wells located in 31 of 39 states (including Connecticut, where 6 out of 12 wells sampled contained one or more VOCs.) (Moran et al. - 2002).

Despite the concerns, samples of ground water from rural, self-supplied domestic wells often did not contain VOCs, and where VOCs were detected, the occurrence and concentration levels were low. Solvents were the most frequently detected VOC group, and were found in 4.6% of samples at an assessment level of 0.2µg/L. However, only 1.4% of samples had one or more VOC concentrations that exceeded a federally established drinking water standard, a health criterion, or both, and only 0.1% of samples had VOC concentrations that exceeded a taste/odor threshold (Moran, et al. - *ibid.*) In general, user education on minimizing the discharge of VOCs' to an OWRS is recommended.

It should be anticipated that when domestic wastewater is discharged to a large-scale SWAS, not all synthetic organic chemicals may be removed by microbial action, and some may reach and mix with the ground water. In such cases, it is possible that the resulting concentrations may reach levels that will have an adverse impact on human health and/or the environment. This may be particularly true for wastewaters containing synthetic organic chemicals on a more or less regular basis. Such wastewaters may include, for example, those discharged from food preparation and serving facilities (e.g.: restaurants, multiple residential dwelling facilities with common dining facilities); multiple residential dwelling facilities that include beauty parlors and hobby shops; and convalescent care facilities. In such cases, methods for enhanced pretreatment of the wastewater to remove toxic synthetic organic chemicals may be necessary before the wastewater is discharged to a SWAS.

It is vitally important to limit the infiltrative surface loading rate of pollutants that exert an oxygen demand to that which has been found by experience to enable the soil to sustain, on a long-term basis, the aerobic environment needed to degrade such pollutants. Failure to do this will result in overwhelming the soil's capacity to renovate the wastewater and cause contamination of the ground water. A discussion of surface loading rates is given in Section X of this document.

F. Nutrients

1. General

The accumulation of nutrients in lakes or other bodies of water results in a process called eutrophication. It can result from natural or anthropogenic processes. The critical nutrients are nitrogen and phosphorus (P). Eutrophication in fresh waters is typically caused by relatively low phosphate concentrations and results in depressed oxygen levels and excessive growth of plants and algae. Phosphorus is usually the limiting nutrient in eutrophication of freshwater bodies. Depressed oxygen levels may result in fish kills of desirable fish stock and their replacement with less desirable fish. Excessive growth of plants and algae can result in development of unsightly scum on the water surface and limit recreational uses. Decaying mats of dead plants and algae can produce foul tastes and odors. Phosphorus, like nitrogen, is critical for key life processes but, unlike nitrate-nitrogen, phosphates are not known to cause adverse health effects (U.S. EPA- 1975; Tyler, E.J., et. al.- 1977). Phosphates have been determined to be generally safe by the U.S. Food and Drug Administration.

Nitrogen is essential to the growth and reproduction of phytoplankton. In saline bays and estuaries, nitrogen is the limiting nutrient. In the presence of an over abundance of nitrogen, organisms such as algae (phytoplankton) and floating, submerged or emergent aquatic vegetation (macrophytes) can proliferate in these water bodies. This can accelerate the natural processes of eutrophication.

The death and decay of excessive algae results in oxygen depletion, a condition that is inimical to fish and other aquatic life that require oxygen to survive. The decay of organic sediment under anoxic conditions can also result in the release of ammonia, which can have a toxic effect on aquatic life, as discussed elsewhere herein. The adverse ecological effects of high nitrogen loads to The Long Island Sound, which stimulate phytoplankton blooms, leading to hypoxia (dissolved oxygen (DO) concentration of 3 mg/l or less), have been well documented (LISS-1990, CT DEP-1998).

Health problems can occur when water that contains nitrates in excess of 10 mg/l, (expressed as nitrate-nitrogen, or $\text{NO}_3\text{-N}$), is consumed by infants, either by direct ingestion, as a result of its use in preparing baby formulas, or to a fetus in a pregnant woman. Nitrate is reduced in the baby's body to nitrite. Nitrite is able to oxidize ferrous iron in hemoglobin to ferric iron and convert hemoglobin (the blood pigment that carries oxygen from the lungs to tissue) to methemoglobin that is incapable of carrying molecular oxygen to tissue. This condition, known as methemoglobinemia (infant cyanosis, or "blue baby disease"), can result in suffocation and is particularly toxic to infants less than three months old.

Methemoglobinemia can also occur in older children and adults if sufficient nitrate is ingested (Bitton and Gerba, 1994; Ammann-1995). Nitrite is also reputed to induce human gastric cancer (Lee, et al.- 1995). The U.S. EPA has established a maximum pollutant level (MCL) of 10 mg/l of nitrate, expressed as $\text{NO}_3\text{-N}$, for drinking water supplies.

2. Nitrogen

Nitrogen is one of two most prominent nutrients in pretreated wastewater discharged to the ground water (the other being phosphorus), and its fate and transport in the soil/ground water regime is of considerable concern when designing OWRS. Concentrations of total nitrogen (TN) in septic tank effluent (STE) typically range from 40-80 mg/l or more, depending upon the source of the wastewater. Sources of wastewater containing higher percentages of toilet/urinal wastes (blackwater) than typical residential septic tank effluent can have much higher TN concentrations.

Most of the nitrogen in wastewater receiving pretreatment in a septic tank is in the form of the ammonium ion (NH_4), with some organic nitrogen, and sometimes trace-to-small amounts of nitrite (NO_2) and nitrate (NO_3) also present. In a conventional OWRS that has an aerobic soil zone beneath the SWAS, ammonium and organic nitrogen are rapidly converted to nitrate. Organic nitrogen must first be mineralized (converted to the inorganic form) by microbial action to ammonium, which takes place in the septic tank and in the biomat, before it is oxidized to nitrate by autotrophic bacteria in the aerobic unsaturated zone.

Where conditions are favorable, various processes remove some of the nitrate. The most significant of these processes is biological denitrification, the reduction of nitrates to nitrogen gas by the metabolic processes of facultative microbes under anoxic conditions. The gaseous nitrogen is then released into the atmosphere via the unsaturated soil pores in the unsaturated zone. However, where conditions are not favorable for the denitrification process (the usual case), nitrate, being very soluble and chemically inactive, may easily percolate down to, mingle, and move with the ground water to points of concern such as drinking water wells and surface waters. The presence of nitrates in both ground water and surface water in concentrations significantly greater than natural background levels can lead to environmental problems.

Up to 20 percent or more of the total nitrogen in raw domestic wastewater can be removed in the septic tank by sedimentation and microbial assimilation (Hardesty, 1974; Laak-1986; Pell and Nyberg-1989, Long-1995). However, where most of the nitrogen enters the septic tank in dissolved forms, as may be the case for wastewaters from schools and domestic wastewater from commercial establishments and industrial facilities (where urine may be the main contribution), the amount removed will be much lower, as sedimentation will not be a significant factor. The remaining nitrogen is discharged with the septic tank effluent to the SWAS.

The fate of the remaining nitrogen depends upon a number of mechanisms and processes, including mineralization, adsorption, plant uptake, volatilization, fixation, immobilization, nitrification and denitrification. These processes in turn depend upon such factors as; soil pH, temperature, moisture, oxidation-reduction (redox) potential, oxygen present in the soil gases, presence and type of organic matter in the soil, soil cation exchange capacity, and microbial populations. In a properly functioning SWAS, 15 to 25 percent of the nitrogen remaining in the septic tank effluent may be removed (Laak – 1986; Long, 1995; Wilhelm et al. – 1996; Crites & Tchobanoglous - 1998).

Mineralization of nitrogen, the conversion of organic nitrogen to inorganic nitrogen (predominantly ammonium) by biological action occurs both in the septic tank and at the biomat in the SWAS, and very little organic nitrogen is found in the wastewater after it flows through the biomat.

Adsorption of ammonium via soil cation exchange may play a role in nitrogen removal, but nitrogen so adsorbed is subject to subsequent desorption and leaching. In addition, eventually a state of equilibrium may become established as all of the cation exchange sites are occupied. When this occurs, desorbed ammonium is replaced with new ammonium cations, and no net removal of ammonium occurs (Magdoff et. al.-1974; Sikora and Corey-1976; Brown, et al.-1978; Brown et al.-1984). Thus, ammonia-nitrogen may remain in ground water that discharges to surface water bodies.

Ammonia is reported to be toxic to aquatic life at very low concentrations of less than 1 mg/L (Laak-1986; U.S.EPA-1993). The EPA criteria for ambient water quality, as well as modified-state criteria, give both maximum total and unionized (free) ammonia levels as a function of pH and temperature. The maximum one-hour average in-stream concentrations of un-ionized ammonia-nitrogen (NH₃) permissible in a three-year period are all under 1 mg/L. The maximum four-day average concentrations for the same are all under 0.1 mg/L (USEPA-1985; USEPA-1993).

The acute toxicity of NH_3 has been shown to increase as pH and temperature decrease. Thus, if nitrification does not occur due to the existence of anaerobic conditions beneath the SWAS, and small amounts of free ammonia persist in the ground water, an adverse effect on aquatic life could result where the ground water discharges to nearby surface waters.

Plant uptake of some of the nitrogen may occur, provided the [SWAS] is within the root zone of the plants, but the amount of nitrogen discharged to a [SWAS] greatly exceeds that which can normally be utilized by nearby plants (Sikora-1976). Plant uptake is usually visually evident from the distinctively greener grass that grows above a SWAS where the effluent can rise into the root zone. This situation may occur when a SWAS malfunctions and floods the surface or near surface, or when a normally operating SWAS has been constructed at a shallow depth below ground surface. However, most of the pretreated wastewater is discharged below the root zone of local vegetation; also, such uptake essentially ceases during the dormant season. Further, unless the vegetation is harvested, it is likely that N will be recycled to the soil as the vegetation decays during the dormant season.

Volatilization of ammonium is only significant at high pH values (≥ 9.5), which seldom exist in and beneath a SWAS. Fixation occurs when ammonium ions become trapped between intercellular layers of clay. Volatilization and fixation are not thought to be significant nitrogen removal processes (Lance-1972).

Immobilization occurs as the microorganisms engaged in removing organic matter incorporate nitrogen in their cells during synthesis reactions. This may account for five to ten percent, or less, of nitrogen removal (Lance -1972). Research has shown that nitrogen incorporated into microbes is held in a rather stable form (Laak-1986).

In a properly functioning SWAS, underlain by an ample depth of unsaturated aerobic soil, almost complete oxidation of ammonium to nitrate usually occurs within 30 - 60 cm (1-2 ft.) of unsaturated soil below the bottom of the leaching system due to the metabolic action of nitrifying bacteria. This usually occurs within a few hours of the exposure of ammonium to an aerobic soil environment (Anderson, et al.-1994; Duncan, et al.-1994; Long -1995). Ammonium is first oxidized to nitrites and the nitrites are subsequently oxidized rapidly to nitrates. If dissolved oxygen is present in the effluent when it reaches the water table, or if the background ground water contains appreciable dissolved oxygen, aerobic oxidation of ammonium may continue in the saturated zone (Wilhelm, et al.-1994).

It should be noted that the necessity for aerobic, unsaturated soil conditions requires that the SWAS not be installed too deeply into the soil, since the oxygen present in the unsaturated soil voids decreases rapidly with depth below ground surface. Below about 40 cm (16 in.) from the surface, the rate of oxygen diffusion decreases exponentially (Otis-1997). Likewise, the placement of a dense layer of soil or pavement above the [SSAS] will severely restrict the transfer of oxygen into the soil (Long-1995).

If conditions are favorable for denitrification (presence of a suitable carbon source, facultative heterotrophic bacteria, and anoxic or anaerobic conditions), some of the nitrate may be denitrified. Very little denitrification will take place in clean sands because of the lack of organic carbon. Some small amount of denitrification may take place in saturated micro-sites between the soil grains (Sextone et al. 1985; Long-1995) where the traces of dissolved organic carbon in the ground water may be sufficient to support the denitrification process. Crites and Tchobanoglous (1998) indicated that about 15% of the nitrate is denitrified in sandy, well-drained soils and 25% in heavier soils.

Nitrate removal from wastewater by denitrification is considered to be rare in aquifers below SWAS (Wilhelm et al.-1994) and most investigators have presumed that dilution by ground water is the predominant mechanism that significantly lowers the nitrate-nitrogen concentration in the ground water. Recent studies have indicated that, in some cases, dilution of nitrates (and other constituents of wastewater) below a SWAS may be much less than posited in previous decades (ibid.) Most investigators have indicated that, generally, any remaining nitrate in the percolate from a SWAS that has not been denitrified before it reaches the ground water will remain unaltered in chemical composition or concentration other than by dilution. In general, nitrate is found to be more mobile in soils with greater moisture content, greater hydraulic conductivity, coarser texture and greater structure.

On the other hand, there is evidence that substantial denitrification may take place where nitrate laden ground water flows through saturated soils with significant readily assimilable (labile) organic carbon content, such as those that exist in wetlands and beneath some water bodies (Robertson, et al. 1991; Korom-1992; Long-1995). Denitrification can also be caused by the action of certain autotrophic bacteria using reduced iron and sulfide as electron donors in the absence of organic carbon (Korom, ibid). However, current capabilities to predict an aquifer's denitrification characteristics are site specific at best (Korom-ibid.).

Nitrogen also reaches the ground water from other sources such as decomposing plants and animals, animal wastes, application of fertilizers for lawn care and agricultural purposes, bacterial action in soil, and direct deposition from the atmosphere.

3. Phosphorus

Phosphorus (P) is the other prominent nutrient in wastewater discharged to the ground water. Phosphorus occurs in natural waters and in wastewaters almost solely as phosphates ($\text{PO}_4\text{-P}$) (Standard Methods-1995). The principal sources of $\text{PO}_4\text{-P}$ in domestic wastewater are human waste, food wastes, toothpaste, pharmaceuticals, detergents (particularly dishwashing detergents), and food-treating compounds. Phosphates in wastewater may include orthophosphates, condensed phosphates (polyphosphates) and organically bound phosphates.

Since in most cases ground water will eventually reach a surface water body, it is important that the phosphorus concentration in the percolate from a SWAS be reduced to background levels in the ground water prior to the ground water reaching a point of concern. Laak (1986) reported that natural ground waters contain 0.01-0.06 mg/l of $\text{PO}_4\text{-P}$, while Reneau, et al (1989) reported that $\text{PO}_4\text{-P}$ concentrations in shallow groundwater are

normally low, with values ranging from 0.005 mg/l to 0.1 mg/l. The PO₄-P concentration in ground water samples in a forested site in eastern Connecticut were found to range from 0.02 to 0.04 mg PO₄-P /L (Pietras-1981), while another study conducted in the Eastern Highlands and Central Lowlands of Connecticut found the mean concentration of PO₄-P in control wells installed up-gradient of on-site systems ranged from 0.02 to 0.06 mg/L (Luce and Welling-1983). U.S. EPA (1986) recommended that to control algal growth, total phosphorus (as P) should not exceed 0.05 mg/L if streams discharge directly to lakes or reservoirs, 0.025 mg/L within a lake or reservoir, and 0.1 mg/L in streams or flowing waters not discharging into lakes or reservoirs. Generally, surface waters maintained at 0.01 to 0.03 mg/L of total P tend to remain uncontaminated by algal blooms or excessive macrophytes.

Septic tank effluent (STE) contains total PO₄-P concentrations ranging between 3–20 mg/l depending upon the source of the wastewater. (The Soap and Detergent Association -1991; Wilhelm et al.-1994; Robertson, W. D. et al.-1998; Crites and Tchobanoglous -1998). Currently, raw sewage total PO₄-P concentrations are usually lower. This decrease has been due to declines in the PO₄-P content of powdered detergents, (in some cases due to regulation of the P content), a significant increase in consumer use of liquid laundry detergents, which do not contain P (Soap and Detergent Association- *ibid.*) and in some cases due to the regulation of the P content.

Because the phosphorus content of detergents is regulated in Connecticut, it can be expected that the total phosphorus concentration in Connecticut domestic wastewater would be in the mid-to-low end of the range given above. (In Connecticut, Sec. 22a-462 of the Connecticut General Statutes limits the phosphorus content in detergents. However, detergents used for medical, scientific or special engineering purposes or for use in machine dishwashers, dairy equipment, beverage equipment, food processing equipment and industrial cleaning equipment are exempt from this limitation.) Therefore, the estimated P content in the wastewater from such sources should be based on actual sampling and testing of the existing facility or, for new facilities, from facilities similar to that which is being proposed to be served.

Within a septic tank, most organic phosphorus and polyphosphates are converted to inorganic soluble orthophosphates during the anaerobic decomposition process that occurs in the tank, with some organic phosphorus also being present in particulate form (Sikora and Corey -1976). Some investigators indicated that approximately 20-30% or more of the total phosphorus in raw wastewater is removed via sludge that accumulates in the bottom of the tank (Bicki, et al.-1984; Pell and Nyberg -1989). On the other hand, other investigators have indicated a much lower percentage removal of P in the septic tank.

Orthophosphate (PO₄³⁻) is the most stable configuration of phosphorus in the soil (USEPA-1977). Organic phosphates are much more mobile than inorganic phosphates and can move rapidly through soil systems. To remove organic phosphates from solution using a soil system, the organic phosphate must be physically filtered and held for sufficient time to allow decomposition of the phosphate compound to an inorganic form (U.S. EPA -1978). The conversion of organic P remaining in the septic tank effluent continues to a lesser degree in the biomat, where additional conversion of organic P to soluble orthophosphates takes place (Wilhelm, et al.-1994).

In addition to the contribution resulting from wastewater discharged into the ground, P reaches the ground water from other sources. Such sources include background P resulting from the natural erosion of rock containing P compounds, animal wastes, decay of vegetation, and application of fertilizers for lawn care and agricultural purposes. P in fertilizers is usually taken up in the upper layers of soil, and generally does not reach the ground water unless excess amounts are used on a long-term basis. Except in active livestock farming operations, animal wastes are a minor source of P in the ground water.

The soil's ability to remove phosphorus from the wastewater percolating from the SWAS is related to its sorptive capacity. The term "sorption" here refers to any process - physical, chemical, or biological-which causes phosphorus to be lost from the soil solution. It includes such processes as adsorption, absorption, chemisorption and precipitation by chemical reaction.

Some biological uptake of phosphorus by soil microorganisms and plants can also occur. However, the phosphorus uptake by microorganisms is small compared to the amount of phosphorus in domestic wastewater. The phosphorus uptake by plants can be significant during the growing season provided the SWAS is installed within the root zones of the plants; however, most systems are installed below that zone. Further, if the plant growth is not harvested and removed from the site, it is likely that the phosphorus will be recycled to the soil as the plant growth decays during the dormant season. Therefore, biological uptake of phosphorus-laden wastewater discharged to the subsurface is not likely to be a significant method of phosphorus immobilization.

The fate and transport of P in wastewaters applied to soils has been extensively studied. The ability of a soil to remove wastewater P from solutions passing through the soil matrix is primarily related to the formation of relatively insoluble phosphate (PO_4) compounds of iron, aluminum and calcium (U.S. EPA -1975).

Most P in orthophosphate form is readily adsorbed to soils that contain reactive iron (Fe) or aluminum (Al) or calcium carbonates (CaCO_3). Reactive iron and aluminum surfaces can occur at the broken edges of crystalline clay minerals, as surface coatings of oxides and hydroxides and of amorphous silicates. Aluminum in the form of positively charged hydroxide polymers, and as an exchangeable ion in acid soils can also adsorb phosphorus. Reactive calcium surfaces are mainly found on solid calcium carbonates and calcium-magnesium carbonates. Organic or mineral soils with minor amounts of Fe and Al show minimal P sorption capacity. In basic soils, calcium phosphates control the P in solution. Calcium compounds predominate above pH 6 to 7, and iron and aluminum compounds predominate below pH 6 to 7. P in orthophosphate form can also combine with silicate materials (compounds containing silicon, oxygen, and one or more metals).

Therefore, in most soils in which Fe and Al are present in a reactive form, or CaCO_3 is present, and flow rates are minimal, phosphorus (P) movement is minimal and concerns of pollution to ground or surface waters from P applied via an SWAS are unfounded. However, pollution of ground water with P can occur in cases where: a.) water tables are shallow; b) soils are coarse textured; c.) flow rates are increased due to strong soil structure; d.) loading rates are high; e.) soils have a low P sorption capacity; f.) the capacity of a soil to immobilize P has been met (VA Dept. of Health -1990).

A major factor contributing to P movement in soil is the flow rate. Increased flow rates are generally associated with soils of coarse texture, strong structure or macro voids associated with biological activity (which provide preferential flow pathways), or high water tables. Thus there is less opportunity for P to be adsorbed to the soil particles and then precipitate with the Fe, Al, or CaCO₃ present in the soil.

Phosphorus that has previously been adsorbed can be desorbed under certain conditions. Desorption of P is always much slower than adsorption but the effect can be considerable when anaerobic conditions exist, organic ions are present, or when the concentration of P in the soil solution is very dilute (VA Dept. of Health - 1990).

Following adsorption, P may precipitate to a separate mineral form. Precipitation reactions occur with soluble iron, aluminum and calcium. Particles of phosphate compounds can also form by separation of adsorbed phosphorus along with iron, aluminum or calcium from solid surfaces (U.S. EPA - 1977).

While precipitation reactions are usually considered permanent, they are reversible, particularly if significant changes should occur in pH, oxidation-reduction (redox) potential, soil solution composition of aluminum, iron or calcium carbonate, or ionic strength (Gold and Sims -2002) or when saturated conditions are present.

Phosphorus removals in the subsurface soils can range from 70 to 99%, depending on the physical and chemical characteristics of the soil. Therefore, the mass and characteristics of soil in contact with the wastewater limit the long-term capacity for phosphorus removal. Removals are related also to the residence time of the wastewater, the travel distance, climatic and other environmental conditions (U.S. EPA-1981).

In the past, it had been assumed that while it was possible that P could move through the soil and reach the ground water, this was not a major concern since P could be easily retained in the soils underlying the SWAS due to chemical changes and adsorption. Many studies that monitored P removal from wastewater discharged to a SWAS documented high P removal in close distance from the SWAS. However, concern had been expressed that this is not necessarily true with respect to coarse-grained soils with low clay and reactive metal content, high pH, and with continually saturated anaerobic soils (Hill and Sawhney-1981). In recent times, the expectations for some environmental impact by P in the ground water have become much stronger. Fairly recent studies have confirmed that P is in fact mobile in such soils and, under such conditions, can travel significant distances (tens of meters) over a period of one or more decades (Wilhelm, et al- 1996; Robertson, et al.-1998; Robertson and Harman-1999).

In numerous studies, P derived from an SWAS has been detected above background levels in ground water adjacent to the SWAS under conditions of saturated flow, due to high water tables or high hydraulic loading rates. However, P concentration in ground water is found to decrease with distance from a SWAS, because P is also capable of undergoing sorption and precipitation in the ground water zone. One study found that passage of effluent through approximately 26-ft (8-m) of somewhat poor to poorly drained soil under

water-unsaturated conditions resulted in a 99% reduction in the P concentration of the ground water. However, under conditions of saturated flow, passage of effluent through 78-ft (30-m) of soil was required before comparable reductions were noted. Thus, P removal in saturated soil is much slower than in unsaturated soil (Reneau-1979).

There are a number of factors that can effect the fate and transport of P in a soil. Some of these factors are beyond the control of a designer of an SWAS, while others can be controlled in order to optimize the immobilization of P in the soil.

Factors that effect the fate and transport of phosphorus in a soil include:

- Physical characteristics of the soil
- Chemical characteristics of the soil
- Temperature of the soil
- Chemical properties of the wastewater
- **Rate of application of P to the soil**
- **Contact time of P solution with the soil**
- **Thickness of unsaturated zone**
- **Degree of oxidation of wastewater reaching the soil**
- **Oxygen levels in the subsurface**
- **Travel distance in the saturated soil**
- **Repeated wetting and drying of the soil.**

For a given site, those factors that can be controlled are printed in bold lettering in the listing given above. Also, where fill systems are used, the designer also has some limited control over the physical and chemical characteristics of the soil. Examples of methods to control such factors are given on the following page.

Limiting the rate at which P is applied to the soil involves adjusting the infiltrative surface P loading rate to that of the soil's long-term P sorption rate. Limiting the infiltrative surface hydraulic loading rate can control the contact time in the unsaturated zone. Constructing an SWAS at a sufficient height above the mounded seasonally high ground water table can control the thickness of the unsaturated zone. The degree of oxidation of the effluent reaching the soil can be controlled by limiting the infiltrative surface organic loading rate and, if necessary, by providing enhanced pretreatment of the wastewater.

Installing the SWAS at a shallow depth below the finished ground surface, avoiding placement of an impervious surface over the SWAS, and limiting the hydraulic loading to a small fraction of the soil's hydraulic conductivity will permit atmospheric oxygen to reach the subsurface via the unsaturated soil pores. Providing sufficient horizontal separating distance between the SWAS and a point of concern can control the travel distance in the saturated soil and thus increase the contact time of P with the reactive soil particles. Where fill systems are used, fill material can be chosen with respect to both its physical (texture) and its chemical characteristics (P sorption capacity) as well as its hydraulic capacity. [Note that many of the factors that effect the fate and transport of P also effect the fate and transport of other pollutants contained in the wastewater discharged to a SWAS, such as organics, nitrogen, pathogens and toxic metals.]

In order to complete the design of a SWAS, it is necessary to know the amount of phosphorus that can be sorbed to the soil particles, and the volume of soil available for sorption. The phosphorus sorption capacity of a soil is typically determined by the use of batch equilibrium experiments. Samples of the soil are added to solutions containing known concentrations of phosphorus. After the soil is mixed into the solution and allowed to come into equilibrium for a period of time (up to several days), the solution is filtered and the filtrate is tested for phosphorus. The difference between the initial and final solution concentrations is the amount adsorbed for a given time. The data obtained from these experiments is used to generate adsorption isotherms. These isotherms are plots of the amount of P adsorbed by a soil vs. the P concentration in each solution. The phosphorus sorption capacity thus determined is usually expressed as mg P removed/100 g of soil.

For example, Sawhney and Hill (1975) determined the P sorption capacity of six major soils in Connecticut from sorption isotherms based on short term (36-48 hours) laboratory P sorption experiments on soil samples obtained from the B2(see appendix for definition) horizons. The results were as follows:

<u>Soil Name</u>	<u>Parent Material</u>	<u>Sorption Capacity, mg/100g Soil</u>
Merrimac	Sandy, gravelly terraces	9.0
Stockbridge	Firm limestone till	14.5
Buxton	Lacustrine silts and clays	20.0
Charlton	Loose till of granite and gneiss	21.8
Cheshire	Loose till of Triassic sandstone and shale	27.5
Paxton	Compact till of gneiss and schist	29.0

Based on analysis of samples from operating drain fields, Sawhney and Hill (ibid.) concluded that most P in wastewater is sorbed within a shorter distance from the point of application than simple laboratory sorption experiments would indicate. They opined that P sorption sites regenerated with time. Regeneration was confirmed in further laboratory experiments. Soils that had been successively treated with P solution showed reduced P sorption capacity but regained the capacity to sorb P after drying and wetting cycles. Thus they stated that phosphate sorption capacities of soils are greater than simple laboratory experiments indicate.

[N.B. The soils used in the tests were those from the B-horizons, which usually contain the most reactive soil particles and minerals. Where a SWAS is located below the B-horizon, it is probable that the P sorption capacity will be considerably less than if it had been located in the B-horizon.]

Important considerations in phosphorus removal are slow reactions between phosphorus and cations present in the soil that may “free up” previously used adsorption sites for additional phosphorus retention. However, these slow reactions are not modeled by isotherm experiments. The slow reactions involve the formation of precipitates of limited solubility and the regeneration of adsorptive surfaces that are then available to adsorb additional phosphate (U.S. EPA-1977). Therefore, the use of adsorption isotherms as a measure of the phosphorus immobilization capacity of a soil significantly underestimates

that capacity. Actual phosphorus retention may be from 2 to 5 times the value obtained from analysis of the adsorption isotherms (Tofflemire and Chen-1977). Thus, the use of the adsorption capacity determined from isotherm experiments will be conservative. However, the use of the isotherm adsorption capacity will provide a margin of safety that is warranted, given the heterogeneity encountered in most Connecticut soil deposits and the recent concerns with respect to P mobility by various investigators. (Hill and Sawhney-1981; Wilhelm, et al- 1996; Robertson, et al.-1998; Robertson and Harman-1999).

G. Pathogens

Pathogens contained in domestic wastewater include various bacteria, parasitic protozoa, parasitic worms (helminths) and viruses. These pathogens can cause infection and disease in humans, are excreted from the human body, and are contained in domestic wastewater discharged to the subsurface via a septic tank and SWAS. Virtually all of these pathogens, with the exception of some helminths, are microscopic in size and cannot be seen without the aid of either an optical microscope or an electron microscope. Accordingly, pathogens are commonly referred to as pathogenic microorganisms.

The U.S. EPA indicates that over one-half of the waterborne disease outbreaks in the United States are due to the consumption of contaminated ground water. While some of these outbreaks are caused by chemical contamination, most are caused by consumption of groundwater that has been contaminated due to the presence of pathogenic microorganisms in domestic wastewater that has been discharged onto or into the soil.

Reported occurrences of drinking-water related waterborne disease outbreaks in the U.S. during 1999 and 2000 more than doubled over the previous two-year reporting period, mostly among untreated private wells, according to the Centers for Disease Control and Prevention (CDC-2002). The CDC report shows that 25 states reported 39 outbreaks that sickened 2068 people and killed two. All but two of the outbreaks were linked to microbial pathogens. Eleven were associated with community water systems, 11 with non-community systems, and 17 with private supplies. Of the community systems, five were attributed to treatment problems, five to the distribution system, and one to untreated ground water. While no outbreaks were reported in Connecticut, the potential for such outbreaks cannot be disregarded.

All pathogenic microorganisms, except for the viruses, are living organisms. They can metabolize substances for food and energy, require water to exist, and can reproduce. As is the case for all living organisms, they eventually die. However, viruses are different. Outside of a host cell, they are inert, have no metabolism, cannot reproduce or move about on their own. When adverse conditions occur which result in destruction of the viruses, they do not “die” but become inactivated, and thus are no longer viable and able to infect a living organism. Therefore, the terms inactivate, and inactivation, refer to the destruction or decay of viruses, whereas the terms die, die-off, or death ordinarily refer to the living pathogens.

Viruses in ground water are of major concern to public health and environmental agencies. This is because of their ability to survive for long periods of time in the subsurface and still remain infectious, and the very small number (as little as one virulent particle, in some cases) thought to cause infection and disease.

Inactivation of viruses contained in domestic wastewater occurs primarily in the biomat that forms at the SWAS-soil infiltrative surfaces, and in the unsaturated soil zone beneath the SWAS. There are a number of factors believed to cause such inactivation. These include climate, the considerable heterogeneity of the soil physicochemical characteristics, the natural processes that tend to remove or degrade pathogens as they travel through the subsurface, and the nature of the pathogen, including its physical, chemical and biological characteristics. However, once viruses reach the ground water, the only factor that has been found to significantly correlate with virus inactivation is temperature. The higher the ground water temperature, the greater the rate of inactivation. Under cold temperature conditions, viruses are known to survive long periods of time (many months and in some cases, years). This is not to say that temperature is the only factor that effects virus survival. Many of the same factors that cause inactivation of viruses in the unsaturated zone are also thought to cause inactivation of viruses after they reach the ground water. However, it has proven difficult to obtain a significant statistical correlation for such factors. Therefore, the travel times set forth in the Design Standards were selected based on the prevailing ground water temperatures in Connecticut, with no allowance for other factors.

Factors that control the adsorption and deactivation of viruses are listed in Table 1, with those factors over which some control can be exercised in design of a SWAS are shown in bold lettering.

In addition to those factors shown in bold typeface in Table 1, factors such as soil texture, soil structure and soil organic content can be controlled to some degree by prohibiting or placing severe restrictions on the installation of a SWAS in certain soils (i.e.: extremely coarse soils, poorly drained to very poorly drained soils, massively structured soils, etc.).

The techniques shown in Table 2 appear to be the most viable means of influencing the adsorption and inactivation of viruses and the die-off of other pathogenic microorganisms. All of the techniques listed in Table 2 interact in attaining the desired result, attenuation of pathogens contained in septic tank effluent before they reach a point of concern. Failure to consider any one technique may have an adverse effect on the desired result regardless of how well the other techniques are applied.

TABLE 1
FACTORS THAT INFLUENCE ADSORPTION AND INACTIVATION OF VIRUSES

<u>Factors Influencing Adsorption</u>	<u>Factors Influencing Inactivation</u>
Climate (Temperature, Precipitation)	Climate (Temperature, Precipitation)
pH	pH
Soil Texture and Structure	Soil Characteristics
% Clay Content and Clay Mineral Species	Antagonism from Soil Microflora
Infiltrative Surface Loading Rate	Adsorption/Desorption
Soil Moisture (Saturated vs. Unsaturated Flow)	Moisture (Dessication)
Soil Gas Oxygen Content	Soil Gas Oxygen Content
Depth to seasonal high ground water table	Time (Travel Time)
Species and Strain of Virus	Species and Strain of Virus
Soil Organic Content	Other natural processes
Cation Exchange Capacity	
Soil Minerals (multivalent cations)	
Ionic Composition of Soil Solution	
Attractive and repulsive forces between soil particles and viruses	
Soil Macropores	

Sources: U.S. EPA-1978; Sobsey et al. -1980; U.S. EPA -1981; -Gerba and Bitton-1984, Newby, et al.-2000.

TABLE 2

TECHNIQUES FOR CONTROLLING FACTORS THAT INFLUENCE THE FATE
AND TRANSPORT OF PATHOGENS IN THE UNSATURATED ZONE.

<u>Technique</u>	<u>Factors</u>
1) Provide Additional Pretreatment	Soil gas oxygen content, aerobic soil, pH, microflora antagonism, virus inactivation.
2) Minimize Depth of SWAS below Ground	Soil gas oxygen content, aerobic soil, microflora antagonism, adsorption.
3) Provide Uniform Flow Distribution	Soil moisture, adsorption.
4) Select proper Infiltrative Surface Hydraulic and Organic Loading Rates	Adsorption, aerobic unsaturated soil, soil moisture.
5) Select proper Linear Hydraulic Loading Rate	Depth of aerobic unsaturated zone, adsorption.
6) Allow for effects of seasonal high ground water table and ground water mounding	Depth of aerobic unsaturated zone, adsorption.
7) Provide adequate Vertical Separating Distance	Depth of aerobic unsaturated zone, adsorption.
8) Provide adequate Horizontal Separating Distance	Travel Time.
9) Provide proper construction methodology	All of the above.

A brief discussion of these factors follows. Detailed discussion on addressing these factors when designing a SWAS will be given in later sections of this document.

Additional Pretreatment

Additional (enhanced) pretreatment, other than by a septic tank, can provide some additional attenuation of pathogens above that provided by a septic tank. Additional pretreatment is often used for reduction of the organic and solids concentrations in the pretreated effluent discharged to a SWAS. Investigators have shown that additional pretreatment beyond that provided by a septic tank will substantially increase the rate of infiltration into the soil surrounding the SWAS by reducing the clogging effect of the biomat. It can also help to maintain aerobic conditions in the unsaturated zone by reducing the oxygen demand caused by the metabolic processes of soil microorganisms that utilize the organic matter as a source of food and energy. This will result in fostering the growth of aerobic soil microflora that will have antagonistic effects on viruses. If disinfection is provided following the additional pretreatment, pathogens can be greatly attenuated.

Depth Below Ground Surface

The depth below ground surface at which a SWAS is installed is important, as it will effect the ability of the unsaturated soil to remain aerobic. (Hurst, et. al.-1980; Lance-1982; Bicki, et al.-1984; Cogger-1989; Otis, et al.-1993; Toze-1997; Cardona-1998)

The transport of oxygen from the atmosphere through the soil and eventually to the onsite system occurs as a result of molecular diffusion, which is a response to the concentration gradient formed by the oxygen rich atmosphere and the oxygen-poor wastewater infiltration site. The oxygen concentration gradient and the distance between the ground surface and the onsite wastewater infiltration site effect the flow rate of oxygen into the system. As the distance between the ground surface and the infiltration site increases, the concentration gradient decreases. The greater the distance, the longer the path the oxygen must travel, causing a decrease in gradient and thus a decrease in the mass flux of oxygen (Erickson and Tyler-2001).

It should also be noted that while oxygen is diffusing downward through the open (non-water filled) soil pores there will be a concurrent diffusion of other gases (e.g. carbon dioxide), released during the metabolism processes of soil microorganisms, in the opposite direction toward the atmosphere. If any denitrification is occurring beneath the SWAS, nitrogen gases are also diffusing upward toward the atmosphere. If anaerobic microsities exist in an otherwise aerobic zone, methane gas (CH₄) as well as carbon dioxide (CO₂) may also be released. (CO₂ is also released during the aerobic oxidation of organic matter, but some of the CO₂ will combine with water to form carbonic acid.) Therefore, it is vitally important that a sufficient amount of open pores remain available so as not to hinder the diffusion processes.

Uniform Flow distribution

The basic objective of flow distribution is to uniformly distribute the septic tank effluent to the infiltrative surfaces of the leaching system so as to maximize the volumetric renovative capacity of the soil. However, there is considerable debate as to whether the distribution should be by means of gravity flow to the various units of the leaching system or by means of a pressure distribution system (PDS). In the latter case, this would require the use of septic tank effluent pumping stations or dosing siphons. The arguments on both sides of this issue appear persuasive. The use of pressure distribution for individual residential subsurface soil absorption systems is arguable because of problems resulting from probable lack of maintenance by individual residence property owners. However, for large systems where the SWAS is extensive and system maintenance is required as part of the permit issued for such systems, pressure distribution may be warranted.

Infiltrative Surface Organic and Hydraulic Loading Rates

- Using an infiltrative surface organic loading rate that will result in a pollutant load applied to the soil in excess of its volumetric capacity to remove or attenuate the pollutants can result in unfavorable conditions developing in and below the SWAS. These unfavorable conditions include depletion of the oxygen in the unsaturated soil beneath the SWAS, and severe clogging of the infiltrative surface. Depletion of the soil oxygen can have a significant adverse effect on the ability of the soil's defense mechanisms to remove or attenuate chemical pollutants and remove or inactivate pathogens. Severe clogging of the infiltrative surface can result in overt failure of the system manifested by wastewater backing up into the facility sanitary drain piping or surfacing of septic tank effluent. A high infiltrative surface hydraulic loading rate can also result in the percolate from the SWAS short-circuiting through large micropores or macropores in the soil, thus reducing the contact time and contact with the soil surface area. This will result in severely reducing the soil's capability for removing and inactivating pollutants. The adverse effects resulting from excessive organic and hydraulic loading rates can be largely avoided by limiting the loading rate to a very small fraction of the soil's saturated hydraulic conductivity. (Siegrist, et al –2000)

Linear loading rates

A high linear loading rate can result in significant mounding of the ground water beneath and immediately down-gradient of a SWAS and may result in the seasonally high ground water table reducing the depth of an unsaturated zone otherwise assumed to be adequate.

Determination of seasonally high ground water elevations

Determination of the seasonal high ground water table (SHWT) is of paramount importance in the design of a SWAS, as it is the basis for establishing an adequate vertical separating distance. Underestimating the height of the SHWT can render an otherwise conservatively selected vertical separating distance ineffective for removal or attenuation of pollutants.

Vertical separating distances

When pretreated domestic wastewater is discharged to the subsurface via a SWAS, it tends to cause a local rise (mounding) of the ground water. This mounding may vary from a very few inches to several feet or more, depending upon the rate of effluent discharge, the configuration of the SWAS, and the characteristics of the subsurface soils. If this mounding is not taken into account, the vertical separating distance may be significantly overestimated. This is particularly important with respect to the large SWAS, and those soils that have restricted hydraulic capabilities. If insufficient vertical separating distance occurs because of failure to take ground water mounding into effect, the result will be a decrease in the volume of unsaturated, aerobic soil available to renovate the wastewater.

Horizontal separating distances

Adequate horizontal separating distance between a SWAS and a point of concern enables any residual pollutants reaching the ground water to be removed or attenuated to the level where the risk to the public health or the environment from the use of the ground water and associated surface waters is acceptable.

Construction methodology

Even the most conservative and meticulous design of a SWAS may not serve to protect the system from failure, or the ground water from contamination, if the implementation of that design during construction is faulty. Proper construction methodology begins before the contractor arrives on the site to install the system by initiation of quality control procedures. This involves such efforts as a review of the contractor's qualifications, a pre-construction meeting to discuss the contractor's duties and obligations, the role of the system designer's field representative, scheduling of the work, and submission and review of shop drawings. Quality control for the project continues until final inspection and approval by the designer and the regulatory agency having jurisdiction.

H. Summary

Natural and synthetic organic chemicals (both dissolved and suspended), nitrogen, and phosphorus are the chemical constituents of domestic wastewater that are of primary concern with respect to contamination of ground water. Heavy metals may also be present, but in very low concentrations that are usually immobilized in the soil. Domestic wastewater contains pathogenic microorganisms, including bacteria, parasitic protozoa, parasitic worms, and viruses. While it is important to consider all of the pathogens, the most important are the viruses that can cause infection and disease in humans. Experience has shown that viruses can exist for long periods of time in the subsurface, particularly under low temperature conditions, and still remain viable long after bacteria and parasites have died off.

When pretreated domestic wastewater (e.g. septic tank effluent) is discharged to the subsurface via a properly designed SWAS, it is renovated as it travels through the biomat that develops at the soil interface with the SWAS. It is further renovated as it travels through aerobic unsaturated soils beneath the SWAS and eventually reaches and commingles with the ground water, and travels to a point of concern, such as a drinking water supply well. The ground water in turn is eventually extracted via wells for various water supply purposes, including drinking water, or discharges to surface waters that are used for many purposes. In this manner, renovated wastewater may be recycled for use many times. Therefore, the chief objective for design, construction, operation and maintenance of a SWAS and its associated pretreatment facilities must be to renovate the wastewater so as to protect the public health and the environment. It is axiomatic that the pretreated wastewater must remain in the soil for a suitable time to permit such renovation to take place.

For the most efficient use of the soil as a wastewater treatment medium, site evaluators and designers need to learn to identify features of soil properties such as those discussed and take them into account when designing soil treatment systems. Soil horizons need to be understood from the perspective of their ability to remove undesirable constituents in wastewater and then system depth, loading rate and method of distribution designed to take maximum advantage of the soil properties that will contribute to achieving the desired level of treatment (Mokma, et al-2001). For example where nutrient removal, particularly P, is of concern, distribution of effluent in the shallow portion of the profile will result in its passage through the most reactive portion of the profile for P removal.

In summary, renovation of wastewater by the soil depends upon the soil's renovative capacity to:

- Allow for organic matter (both natural and synthetic) to be decomposed or mineralized into relatively innocuous substances by indigenous soil microflora.
- Immobilize toxic metals by sorption onto reactive soil particles.
- Immobilize phosphorus by adsorption onto reactive minerals in the soil and precipitation with metal oxides and calcium compounds.
- Immobilize pathogenic microorganisms by filtering and/or by adsorption to soil particles until they ultimately die or become inactivated by antagonistic soil microflora, dessication, and other adverse environmental effects.
- Oxidize ammonia-nitrogen compounds to nitrates in aerobic soil zones and remove some of the nitrates by denitrification in anaerobic microsites and/or anaerobic soils located beneath and downgradient of the aerobic zones. (Dilution of nitrates in the ground water beneath and downgradient of an SWAS is also a factor, but may not always be sufficient to reduce the nitrate concentration to acceptable values.)

To ensure proper functioning of an OWRS:

1. The hydraulic, organic and nutrient loadings on the SWAS should be such that the finite, long term, capacity of the soil to accomplish wastewater renovation is not exceeded.
2. There must be sufficient vertical separation between the bottom of a SWAS and the water table so that an adequate depth of unsaturated aerobic soil will be maintained at all times, including during seasonal high ground water conditions.
 - a. Unsaturated flow beneath a SWAS is important in ensuring slow travel and thus long residence time for pathogenic microorganisms in the unsaturated zone, good aeration, increased opportunity for contact between effluent and soil particles, opportunity for adsorption of pathogenic microorganisms to soil particles, and eventually die-off or inactivation of these pathogens.
 - b. The same conditions resulting from unsaturated flow and the existence of an aerobic environment beneath a SWAS discussed in a. above are also very important for removal of organic compounds, immobilization of phosphorus and heavy metals. Such conditions are also required for conversion (oxidation) of ammonium-nitrogen to nitrates.

The facts discussed time and time again in the literature regarding removal of the most significant pollutants from domestic wastewater discharged to the subsurface are:

- The subsoil horizons that are the most active with respect to wastewater renovation are those that are aerobic, unsaturated, and have been enriched by materials (organic material, clay, iron and aluminum oxides, and calcium carbonates) that have been leached (eluviated) from the overlying topsoil and subsurface soil.
- Most of the wastewater renovation processes occur at the biomat that forms at the SWAS interface with the surrounding soil and in the unsaturated aerobic soil zone beyond the biomat.
- The pollutant loading must not exceed the finite capacity of the soils to effect pollutant attenuation and/or removal. The capacity of the soil should be estimated for each pollutant of interest, and the design of a SWAS should be based on the limiting capacity. (e. g.: Using an infiltrative surface organic loading rate that will result in a pollutant load applied to the soil in excess of the soil's volumetric capacity to remove or attenuate the pollutants can result in unfavorable conditions developing in and below the SWAS. These unfavorable conditions include depletion of the oxygen in the unsaturated soil beneath the SWAS, and severe clogging of the infiltrative surface.)
- The hydraulic loading must not exceed the soil-ground water hydraulic capacity for assimilating the wastewater discharged to the SWAS without surfacing before renovation is complete.

- It is vitally important to maintain an aerobic, unsaturated soil zone of sufficient depth below the SWAS by providing sufficient vertical separating distance between the bottom of the SWAS and the seasonal high ground water table.
- The infiltrative surface hydraulic loading rate must be controlled so as to provide for a slow rate of travel of wastewater through the unsaturated soil zone that will assure an intimate contact of wastewater with soil particles and mitigate against rapid flow through preferential pathways. This is accomplished by limiting the loading rate to a very small fraction of the soil's saturated hydraulic conductivity.
- Adequate horizontal separating distance between the SWAS and a point of concern must be provided to enable any residual pollutants reaching the ground water to be removed or attenuated to the level where the risk to the public health or the environment from the use of the ground water and associated surface waters is acceptable.

These facts should be kept firmly in mind when reviewing the information in the following sections of this document that discuss design, operation, and maintenance of on-site wastewater renovation systems.

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