Hydrological Evaluation of Septic Disposal Field Design in Sloping Terrains

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Abstract: The most common form of onsite domestic wastewater treatment in the United States is the septic system. Although the design of these systems has been well established, no systematic evaluation of septic system performance exists for sloping hardpan soils. In this paper, we develop a simple hydrologic model for assessing the probability of failure for a set of hydrologic conditions, septic loading rates, and soil and landscape parameters that are readily available for sloping soils. To demonstrate the model capabilities, input data for a septic field of a two-person residence in the New York City drinking water basin in the Catskills was utilized. Our analysis showed that the saturated hydraulic conductivity, depth to the impermeable layer, and slope of the drain field are critical parameters to assess in the design and siting of these systems. We concluded that septic systems perform poorly in undulating landscapes where the hydraulic conductivity is low and the impermeable layer is close to the surface. Under prolonged rainfall conditions on these soils, the septic field and downslope field saturate, causing hydraulic failure of the septic system and saturation in the downslope field; as a result, effluent may be routed directly to streams via overland runoff.

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Introduction

The most common form of onsite wastewater treatment is the septic system (Wastewater 1991). Over 50 million people in the United States use septic systems, producing more than 10 billion L of wastewater per day, containing appreciable quantities of pathogens, phosphorus, and nitrate (Gerba et al. 1975; Sawhney and Starr 1977). A typical septic system consists of a watertight septic tank and an effluent disposal drainage field. Floatable waste is trapped inside the septic tank by baffles (Otis 1980a,b; Wastewater 1991). Larger sediments settle out of the water column and are anaerobically digested in the bottom of the septic tank. The drainage field is comprised of a series of narrow, relatively shallow trenches filled with a porous medium. In most cases, perforated drainage pipes are used to distribute the septic tank effluent in the trenches either by way of gravity or through periodic dosing using a siphon or pump. Treatment of wastewater occurs by way of biological, chemical, and physical processes that take place both in the septic tank and in the soil surrounding the disposal field. When designed properly, the disposal field facilitates the infiltration of the effluent into the surrounding soil, where contaminants are removed by natural processes. However, improper site conditions and inappropriate design can lead to system failure and result in poor treatment performance, saturation of the soil profile, and transport of contaminants offsite before complete treatment has occurred.

In general, two types of failure can be distinguished. "Treatment failure" occurs when contaminants are not fully removed from the water because of an insufficient depth of the aerated zone. "Hydraulic failure" happens when the water table inundates the disposal pipes or reaches the ground surface, where overland flow can transport the pollutants directly to the stream without further treatment. Treatment and hydraulic failure can result from the improper siting of septic fields.

Transport of contaminants from septic disposal fields to groundwater via unsaturated flow has been well documented (Robertson 1995; Robertson and Harman 1999; Wilhelm et al. 1994). Gerba et al. (1975) found viruses in well water at distances of 60–120 m from septic fields in saturated soils. Riznyk et al. (1993) found seasonal fluctuations in fecal coliform counts in peat leach fields of Alaska ranging from nondetects to levels similar to those found in tertiary treated wastewater. Nitrate and phosphate are very mobile in septic systems. Wilkinson and Bevins (1999) found that nitrate passing through the root zone is easily leached to shallow groundwater. Measured nitrate concentrations in

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downgradient plumes well exceeded drinking water standards (10 mg/L NO_3^--N) and were documented as high as 30 mg/L at distances upwards of 55 m from the disposal field. Gold et al. (1990) measured mean annual concentrations of 68 mg/L NO_3^--N with an associated mass loss of 48 kg/ha N from septic fields on well drained silt loam or sandy loam soils servicing three-person residences in Rhode Island. Phosphate plume concentrations in groundwater have exceeded drinking water standards (>2 mg/L) at documented distances greater than 25 m from septic disposal fields (Wilhelm et al. 1994). Failures of septic systems have other implications as well. Increased biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) can all negatively affect water quality (Riznyk et al. 1993).

To avoid contamination of local ground and surface waters, selection of the appropriate disposal field configuration is vital. Proper design of a septic effluent disposal field involves the estimation of soil properties, such as slope, depth to groundwater or impermeable layer, and proximity to drinking water supplies, buildings, and other obstructions. Soil type, percolation rate, depth to impermeable layer, and the average water table height are factors that must be considered when determining the suitability of a site for a septic system. Design criteria for conventional trench leach fields have been developed for landscapes with deep soils overlying aquifers. General design requirements for conventional systems specify that there should be at least 1 m between the septic effluent distribution pipes and seasonal high groundwater depth (Otis 1980a,b). The New York State (NYS) Department of Health (1996) requires a minimum of 1.2 m of soil above bedrock and seasonal high groundwater table less than 0.6 m from the lowest part of a trench. Day (2004) showed that 96% of the area in the Cannonsville Basin in the Catskills area of New York State had soils that did not meet this criteria. Because the 0.6 m separation distance between the effluent distribution pipes and the groundwater cannot be reasonably assumed in the glaciated regions of New York State, a better criterion to indicate system failure may be when the water table rises to or above the effluent distribution lines in the septic disposal field. When this occurs, a musty or rotten-egg odor (H_2S) usually emanates from the septic system. According to EPA standards, the odor is a good indicator of problems, although it has been reported by field engineers that the smell also occurs in vented well functioning systems. In addition, hydraulic failure on sloping soils can also occur when the septic effluent flows laterally and surfaces downslope of the septic field itself.

The objective of this research is to develop a simple model to evaluate septic system performance in sloping hardpan soils such as those found in the northeast United States. The model simulates water movement, moisture content, and water table height in three fields consisting of the septic effluent disposal field, the adjacent upslope field (which contributes runoff and subsurface flow to the septic field), and downslope field (which receives runoff and subsurface flow from the septic and upslope fields) (Fig. 1). In this paper we will assume that in the septic field, hydraulic failure occurs when the water table is at or above the septic field distribution pipes. Additionally, hydraulic failure in the adjacent upslope and downslope fields is considered and occurs when the water table is 0.2 m or less below the soil surface. The 0.2 m is arbitrary but will assure that the field is trafficable and that there is no short-circuiting of septic tank effluent via quick or overland flow to nearby water bodies.

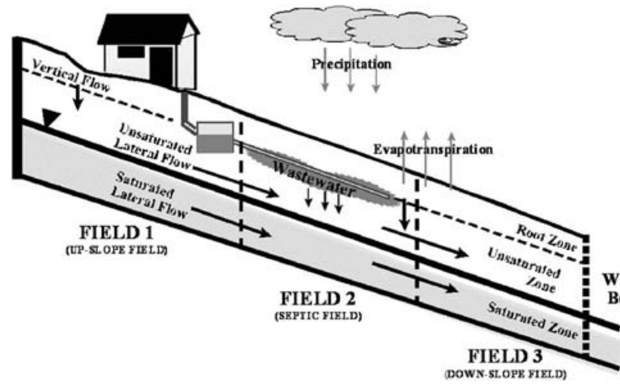

Fig. 1. Schematic drawing of the septic system being studied. From upslope to downslope:Field 1=upslope area; Field 2=septic effluent disposal field; Field 3=downslope area

Model Development

A water budget model was developed to predict the soil moisture status of a septic effluent disposal field and the adjacent upslope and downslope fields on a hill slope with a restrictive layer at a shallow depth below the soil surface. Because lateral flow contributions/effects are significant on shallow sloping soils, both the upslope and downslope portions of the hill slope were included in the simulations. Fig. 1 depicts the system as modeled. Three parts of the hill slope (called "fields") were considered. Field 1, the upslope field, or the contributing area above the septic disposal field, extends to the top of the hill. Thus, there is no inflow from above Field 1. Field 2 contains the septic effluent disposal field and receives both inflow from Field 1 and septic effluent from the residence. Field 3 is downslope from the disposal field and captures all water (either runoff or lateral flow) from upslope. The stream or other water body is situated at the bottom of the slope and receives lateral and overland flow from Field 3, immediately upslope of the water body. Each field is divided into two fixed layers: a root zone and a subroot zone. In the root zone, evapotranspiration is the major loss, followed by seepage from the root zone to the subroot zone. The subroot zone extends from the root zone to the restricting layer. Rain and evapotranspiration are included for all three fields. As a conservative assumption, seepage through the restrictive layer was ignored.

The purpose of the model is to track the height of the water table in each field to assess the probability of failure due to the water table reaching the level of the septic disposal distribution pipes in the septic field or above 0.2 m below the ground surface in the upslope and downslope fields. During dry periods, the water table above the restricting layer can disappear, a result of the evapotranspiration rate and the subsurface lateral outflow exceeding the inflows. During wet periods, the water table may extend up to and above the root zone, inundating the effluent disposal pipes and causing hydraulic failure of the system. Once the water table is at the surface, any excess water becomes overland flow. Despite the shallow soil depth of typical Catskill soils, some waste treatment still occurs under unsaturated conditions due to lateral subsurface flow. We indicate the soil below the groundwater table as the saturated zone and that above the groundwater table as the unsaturated zone (Fig. 1).

Inputs considered are precipitation into the root zone for all three fields and the septic tank effluent discharge into the subroot zone layer of Field 2, while outputs are evapotranspiration from the root zone, vertical flux from the root zone to the subroot zone, the lateral flux between the fields, and finally, the flux out of the downslope end of Field 3. We assume that precipitation infiltrates uniformly over the soil surface and that water is removed from the root zone by evapotranspiration according to the Thornthwaite-Mather procedure (Thornthwaite and Mather 1955; Steenhuis and Van der Molen 1986). Septic tank effluent is added directly to the subroot zone in Field 2 at a rate dependent on the number of persons in the household. At water contents above field capacity in the root zone, the excess water percolates down to the subroot zone. Lateral flow occurs in both the saturated and unsaturated zones and is controlled by the conductivity of the soil and the slope of the land [i.e., the kinematic approximation in Darcy's law (Hillel 1998)].

The general water budget for each of the three fields above the impermeable layer over a period Δt is

$$S_t = S_{t-\Delta t} + (P + W - E_a + Q_{Lu} - Q_{Ld}) \quad (1)$$

where S_t=amount of water stored above the restricting layer per unit area for a field (sum of the water stored in the root zone, S_r, and in the subroot zone, S_s); P=precipitation; W=wastewater input from the septic tank (zero for Fields 1 and 3); E_a=actual evapotranspiration; and Q_{Lu} and Q_{Ld}=lateral flux into the field from upslope and leaving the field in the downslope direction if applicable, respectively. All quantities have units of depth [L^3/L^2 or L] and are given over the time period Δt. In the computer program a time step of one day was used.

To simplify the calculations, the equations for each of the fields are solved sequentially by analytical methods. The moisture removed from the root zone by evapotranspiration is calculated first, followed by the vertical fluxes in and out of the root zone, and finally the lateral flow from the unsaturated and saturated zones to adjacent fields. Both evapotranspiration and rainfall are assumed to occur at the beginning of a time step. These calculations done in sequence do not significantly alter the magnitude of fluxes or soil moisture contents in the fields (Frankenberger et al. 1999).

Evaporative Fluxes

Actual Evapotranspiration (E_a) from the root zone is calculated using the Thornthwaite-Mather procedure (Thornthwaite and Mather 1955; Steenhuis and Van der Molen 1986), where above-field capacity E_a is equal to the potential evapotranspiration (E_p). Potential evapotranspiration rates vary seasonally according to a sinusoidal function that has been fitted against the observed E_p data. Below field capacity, E_a is instantaneously linearly related to the moisture content from E_p at field capacity to zero at the wilting point and can be calculated over a period Δt as

$$E_a = (S_{r,t-\Delta t} - d_r\theta_{r,wp})\left[1 - \exp\left[-\frac{E_p\Delta t}{d_r(\theta_{r,fc} - \theta_{r,wp})}\right]\right] \quad \text{for } \theta_{r,t-\Delta t} < \theta_{r,fc} \quad (2)$$

where $S_{r,t-\Delta t}$=quantity of water stored in the root zone; d_r=depth of the root zone; $\theta_{r,fc}$=field capacity moisture content in the root zone; and $\theta_{r,wp}$=wilting point moisture content in the root zone. E_p is calculated as a sine function of the maximum evapotranspiration occurring in July ($E_{p,\max}$) and the minimum evapotranspiration occurring in January ($E_{p,\min}$):

$$E_p = E_{p,\min} + \frac{E_{p,\max} - E_{p,\min}}{2}\left[1 + \sin\left(\frac{2\pi(N-100)}{365}\right)\right] \quad (3)$$

where N=day of the year. The amount of water stored in the rootzone, $S_{r,t}$ at time t, is then updated as follows:

$$S_{r,t'} = S_{r,t-\Delta t} + P - E_a \quad (4)$$

The subscript t' is used here to indicate that the storage term is still an intermediate. Once all fluxes are calculated, the prime is dropped.

Vertical and Lateral Fluxes

Using the updated soil water content in the root zone [Eq. (4)], the vertical flux between the root zone, the lateral flux in the saturated and unsaturated zones, and the surface runoff are determined next. To simplify the calculation, it is assumed that the soil moisture content for each field is uniform in both the root zone and the unsaturated zone. We also assume that, as long as there is a water table above the restricting layer, the unsaturated moisture content is constant and equal to the saturated moisture content, θ_s, minus the drainable porosity, μ

$$\theta_e = \theta_s - \mu \quad (5)$$

This is termed the equilibrium moisture content, θ_e. The storage of water in the root zone at the equilibrium moisture content, $S_{r,e}$, is

$$S_{r,e} = d_r\theta_e \quad (6)$$

where d_r=depth of the root zone.

To calculate the potential vertical flux from the root zone to the subroot zone, the moisture content in the root zone, $\theta_{r,t'}$, is then compared with the equilibrium moisture content θ_e. When $\theta_{r,t'}$ is higher than field capacity, the vertical flux, q_r[L/T], out of the root zone is

$$q_r = \frac{S_{r,t'} - S_{r,e}}{\Delta t} + w \quad \theta_{r,t} > \theta_e \quad (7)$$

and the moisture content of the root zone is set equal to equilibrium moisture content. When $\theta_{r,t}$ is lower than θ_e, the flux is equal to the household septic effluent flux w, where

$$w = \frac{W}{\Delta t} \quad \theta_{r,t} < \theta_c \quad (8)$$

and

$$\theta_{r,t'} = \frac{S_{r,t'}}{d_r} \quad (9)$$

Note that w=0 in Fields 1 and 3.

Calculations to determine the lateral fluxes under saturated or unsaturated soil profiles are different. The boundary between the saturated and unsaturated zone can be found directly from the total amount of water stored in the soil after the adjustments for evapotranspiration and rainfall have been made

$$d_s = s\frac{S_{t'} - d_T(\theta_s - \mu)}{\mu} \quad \text{for } S_{t'} > d_T(\theta_s - \mu) \quad (10)$$

and

$$d_s = 0 \quad \text{for } S_{t'} \le d_T(\theta_s - \mu) \tag{11}$$

where d_s=depth of the saturated zone above the impermeable layer; and d_T=total soil depth above the impermeable layer.

Lateral fluxes in the unsaturated zone are calculated using an exponential conductivity function of the form:

$$K_\theta = K_s \exp\left(\lambda \frac{\theta_s - \theta}{\theta_s}\right) \tag{12}$$

where K_θ=unsaturated conductivity; K_s=saturated conductivity; λ is a constant in hydraulic conductivity equal to 13 (Steenhuis and Van der Molen 1986); and θ=moisture content of the unsaturated zone.

For a constant uniform vertical and lateral flux from the root zone, the depth of the water table above the impermeable layer at the end of the time step can be found by applying Darcy's law, taking the hydraulic gradient equal to the slope of land surface, α (i.e., kinematic approximation), and neglecting the upslope lateral flux (added at the end of the time step)

$$d_{s,t} = d_{s,t'} \exp\left[-\frac{(K_s - K_\theta)\Delta t \sin\alpha}{\mu L}\right] + \left[\left(q_r - \frac{K_\theta d_T \sin\alpha}{L}\right)\frac{L}{(K_s - K_\theta)\sin\alpha}\right] \times \left[1 - \exp\left[-\frac{(K_s - K_\theta)\Delta t \sin\alpha}{\mu L}\right]\right] \tag{13}$$

where K_θ=conductivity of the unsaturated zone and can be obtained from Eq. (12) by substituting $(\theta_s - \mu)$ for the moisture content. L is the length of the field.

When the subroot zone is unsaturated, the moisture content at the beginning of the time step (Steenhuis and Van der Molen 1986) is

$$\theta_t = \theta_s - \left(\frac{\theta_s}{\lambda}\right)\ln\left[\frac{\lambda K_s \sin\alpha\Delta t}{L\theta_s} + \exp\left(-\lambda\frac{\theta_s - \theta_{t'}}{\theta_s}\right)\right] \tag{14}$$

This formulation neglects any vertical flux in the profile. The lateral flux to the downslope field Q_{Ld} can be calculated by taking the difference between θ_s and $\theta_{t'}$ in Eq. (14) and multiplying it by the volume of the soil. The final step is updating the moisture content in the subroot zone by adding the lateral flux from upslope, or if the soil is unsaturated, the vertical flux from the root zone.

Surface runoff occurs when the water table saturates the soil profile and rises to the land surface. This quantity is equal to all excess fluxes that cannot be stored in the soil. It is routed to the next field and added to the input rainfall amount for the field.

Eqs. (1)–(14) were programmed in Quattro Pro. The program has been saved in Excel format and is available online at ⟨http://www.bee.cornell.edu/swlab/soilwaterweb/index.htm⟩.

Input Data

Model inputs were either taken from easily accessible data source, estimated, or calculated in the model. Many of the inputs were taken directly from the soil survey or previous research done in the watershed and included the depth of the root zone (d_r), depth of the saturated/unsaturated zone (d_T), hydraulic conductivity (K_s), quantity of water stored in the root zone at equilibrium moisture content ($S_{r,e}$), equilibrium moisture content (θ_e), moisture content of the root zone at field capacity ($\theta_{r,fc}$), moisture content of the root zone at wilting point ($\theta_{r,wp}$), saturated moisture content (θ_s), and the drainable porosity (μ). Climatic data from the Delhi weather station located in the center of the Cannonsville Reservoir watershed, a watershed included in the New York City drinking water basin, for the period of April 1996 to August 2000 included the potential evapotranspiration (E_p), maximum potential evapotranspiration in July ($E_{p,\max}$), minimum potential evapotranspiration in January ($E_{p,\min}$), and precipitation (P). The day of the year (N) is used in the Julian counting day formulation, and the time step (t) was selected as one day for use in the model. Estimated data selected to represent conditions in the Catskills included the length of the fields (L) and the wastewater input to the septic field (W). The constant in hydraulic conductivity (λ) was taken from Steenhuis and Van der Molen (1986). All other variables were calculated directly in the model.

Application of Model

There is a great interest in reducing nonpoint-source phosphorus contributions in the New York City watersheds in the Catskills Mountains, especially in the Cannonsville Reservoir basin in Delaware County. Restrictions to limit the quantity of phosphorus discharged to Cannonsville Reservoir can be imposed on the county by the New York City Department of Environmental Protection (NYS-DEP) in order to improve water quality and reduce the occurrence of problems associated with excess algal growth, including disagreeable taste and odor and the production of chlorination by-products. The ultimate measure by which water quality is quantified is an in-reservoir concentration of total phosphorus of $<20\ \mu g/L$ during the growing season. Failing septic tanks are implicated as one of the sources of excess P in the Cannonsville basin (Day 2004). For the last three years, the Cannonsville Reservoir has been just below 20 $\mu g/L$.

Therefore, we used the Cannonsville Reservoir basin as an example of model implementation. The basin is characterized by a rolling landscape with relatively shallow soils over a restrictive glacial till. As mentioned in the introduction, design standards for conventional trench septic effluent leach fields require over 1.2 m (4+ft) of usable soil, which is only met on 4% of the area in the Cannonsville. The model will aid in finding the optimal conditions for siting septic leach fields and in finding further ways to reduce P loading of the reservoir.

In the report of Day (2001), the following pertinent characteristics related to septic tanks were listed. A typical residence in the Catskills area has slightly over two persons, so we investigated the drainage field of a two-person house, assuming that 360 liters (100 gallons) of septic effluent, or wastewater, was added to the field per day, resulting in a uniform depth of 0.5 cm effluent over the entire field with an assumed surface area of 72 m^2. Because septic systems can be located in diverse areas of the landscape, a range of input parameters typical of the Catskill conditions were investigated. We assumed that the perforated pipes were installed at 25 cm below the soil surface and that there is a 1.25 m sand layer (imported, as for typical raised trench leach field design) with a saturated conductivity of 10 m/day below the perforated pipes. The data ranges and "typical values" for the septic field and the fields up- and downslope are listed in Table 1. The "typical values" for the in-situ soils are based on averages of actual measured parameters for the soils in the Catskills and obtained from soil surveys and the various studies carried out in the basin (Frankenberger et al. 1999; Mehta et al. 2004). Septic tank effluent will likely change these values; however, because limited data exists on the effect of effluent on bulk soil properties, we used the

Table 1. List of Parameters, Typical Values Assumed, and Range of Values Used in Sensitivity Analysis

Parameter	Symbol	Typical value			Range modeled
		Field 1	Field 2	Field 3	
Field length for Fields 1, 2, and 3 (m)	L	30	8.5	30	2.5–500
Rooting depth (m)	d_r	0.25	0.25	0.25	
Depth of impermeable layer (m) (below root zone)	d_T	1.25	1.25	1.25	0.25–4.0 m
Field slope (%)	α	4	4	4	1–20%
Moisture content at wilting point ($cm^3\ cm^{-3}$)	θ_{wp}	0.11	0.11	0.11	
Moisture content at field capacity ($cm^3\ cm^{-3}$)	θ_{fc}	0.30	0.30	0.30	
Saturated moisture content ($cm^3\ cm^{-3}$)	θ_s	0.50	0.50	0.50	
Drainable porosity ($cm^3\ cm^{-3}$)	μ	0.1	0.1	0.1	
Saturated hydraulic conductivity (m/d)	K_s	4	10	4	0.5–20 at 4% steps

preceding values in the design of the system. Most hill slope soils in the basin are underlain by glacial till that restricts vertical flow of water. The depth to the restricting layer of 1.5 m outlined by the NYS Department of Health (1996) guidelines represents ideal conditions for septic field installation and served as a starting point for the analysis. We assumed that grass is grown with a root zone of 25 cm. The saturated conductivity of 4 m day^{-1} was used, which is at the high range of the values in the soil survey, but the soil is well structured in the Catskills, and the soil survey is based on disturbed samples, which tends to underestimate permeability (Boll et al. 1998). The drainable porosity was taken at 0.1 $cm^3\ cm^{-3}$, which is reasonable approximation and within the range for well-structured soils. Field capacity, saturated, and wilting point moisture contents were in general agreement with soil survey values (Mehta et al. 2004). The length of the fields assume that the septic field is located at a distance of 30 m from the stream and that a typical upslope contributing length is 30 m.

We first modeled the water table height in the three fields using the default input values. The default values represent the recommended, or in the case of the Catskills, ideal conditions for siting septic systems. The height of the water table for the typical values in Table 1 in each of the fields over the 1,600 day period is depicted in Fig. 2. Failure was tallied in each field, and it occurs when the water table is at or above the septic field distribution pipes in the septic field (Field 2) and when the water table is 0.2 m or less below the soil surface in the upslope and downslope fields (Fields 1 and 3). As expected, the amount of precipitation and evapotranspiration directly affected the water table height. The water table height above the restricting layer was generally lowest in the summer and at times disappeared completely in field

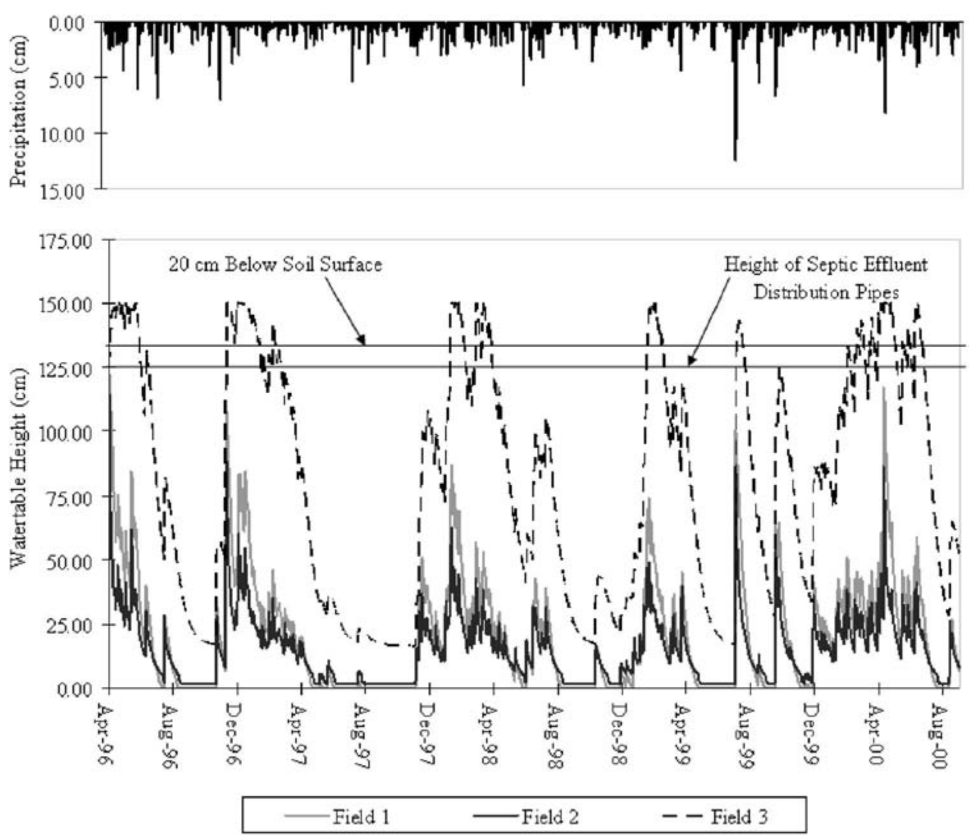

Fig. 2. Precipitation and simulated water table height for Fields 1, 2, and 3 for the period of April 1996 to August 2000

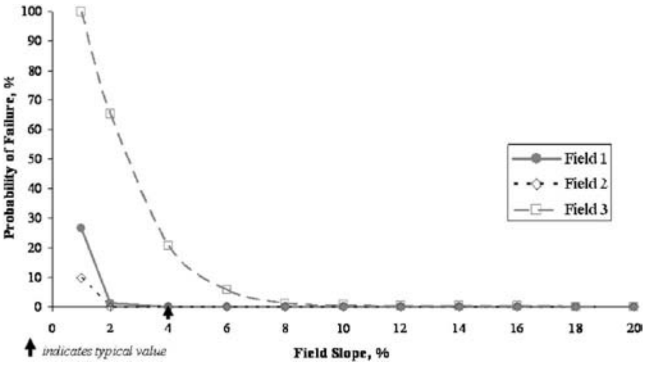

Fig. 3. Probability of failure in Fields 1, 2, and 3 as a consequence of varying the slope uniformly for all three fields. Failure is defined for Fields 1 and 3 when the water table is within 20 cm of the surface and for septic effluent disposal field (Field 2) when the water table exceeds the porous drain pipes.

1, upslope of the septic system. During the summer of 1999, a large storm in June caused the water table to return temporarily in Field 1. The water table downslope of the septic system in Field 3 was, on average, the highest and reached the soil surface at 150 cm several times during the winter and spring months, due to precipitation exceeding E_a and the additional flux from the upslope fields (1 and 2) accumulating (Fig. 2). The water table in the septic field (Field 2) was generally just below the height of Field 1 despite the added septic tank effluent, mainly because the imported soil had a saturated conductivity 2.5 times greater than that of the native soil. Consequently, the water table never reached the level of the perforated pipes in Field 2. Thus, under ideal or recommended site conditions (i.e., adequate soil depth, slope, conductivity, and contributing area), septic systems and septic disposal fields are appropriate. However, only 4% of the basin contains ideal conditions.

Because ideal site conditions for septic disposal fields are rare in the Cannonsville basin, it was informative to examine the effect of the location of the septic system in the landscape as well as the soil properties on the septic system failure rate and/or the number of times the water table is within 20 cm of the soil surface in Field 3. Therefore, we used a sensitivity analysis and varied one parameter while the others were kept fixed. Ranges for the parameters are provided along with typical values in Table 1. The parameters considered are saturated conductivity, subroot zone soil depth, and field length for the upslope (Field 1) (Fig. 4) and downslope (Field 3) (Fig. 6) fields. The plugging of the soil pores with effluent is examined for the disposal field (Field 2) by changing the saturated conductivity of the soil [Fig. 5(c)] in addition to the effect of varying the length of the septic field (Field 2) and the depth of its subroot zone soil on the disposal efficiency [Figs. 5(a and b)]. In all equations where the saturated conductivity appears, it is in combination with the sine of the slope, α, which unlike the other parameters remains uniform for all three fields. Thus, the product $K_s \sin\alpha$ determines the hydraulic behavior of septic effluent disposal, and a decrease in conductivity has the same effect as a decrease in $\sin\alpha$. However, K_s may vary for each field (the effect of which is shown in the figures for each field), while the slope is uniform for all three fields. Fig. 3 describes the result of varying the slope of the septic system landscape. Fields 1 and 2 experience no failure at any slope greater than 4%. However, in Field 3 where flow is not only produced within the field but is collected from the upslope fields, the effect of slope on the field's failure rate is significant, increasing to 100% for slopes less than 1% and decreasing to $<1\%$ for percentage slopes greater than 10.

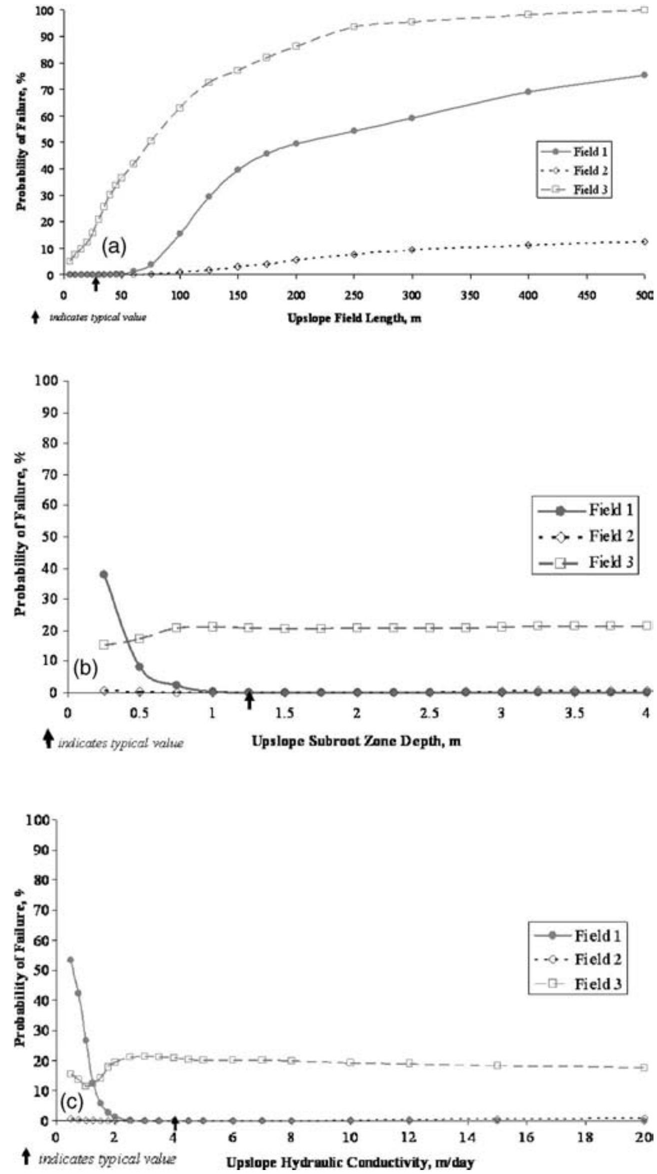

Fig. 4. Probability of failure in Fields 1, 2, and 3 as a consequence of changing the properties in Field 1. Failure is defined for Fields 1 and 3 when the water table is within 20 cm of the surface and for septic effluent disposal field (Field 2) when the water table exceeds the porous drain pipes: (a) upslope field length is varied; (b) upslope field soil depth is varied; (c) upslope field saturated hydraulic conductivity is varied.

The effect of changing the parameter values for Field 1 (upslope field) is shown in Fig. 4 while keeping the remaining parameters for Fields 2 and 3 constant at the typical values of K_s=4 m/day, L=30 m, slope=4%, and d_T=1.25 m (see Table 1). The upslope contributing area (represented by the field length) has a significant effect on the failure rate and to a lesser degree on the septic field itself [Fig. 4(a)]. For an upslope field length of 500 m, the septic field (Field 2) fails 10% of the time while the water table in the downslope field (Field 3) remains within 20 cm of the surface for almost the entire period (based on the long term climatic records for the Catskills used in the analysis). The latter

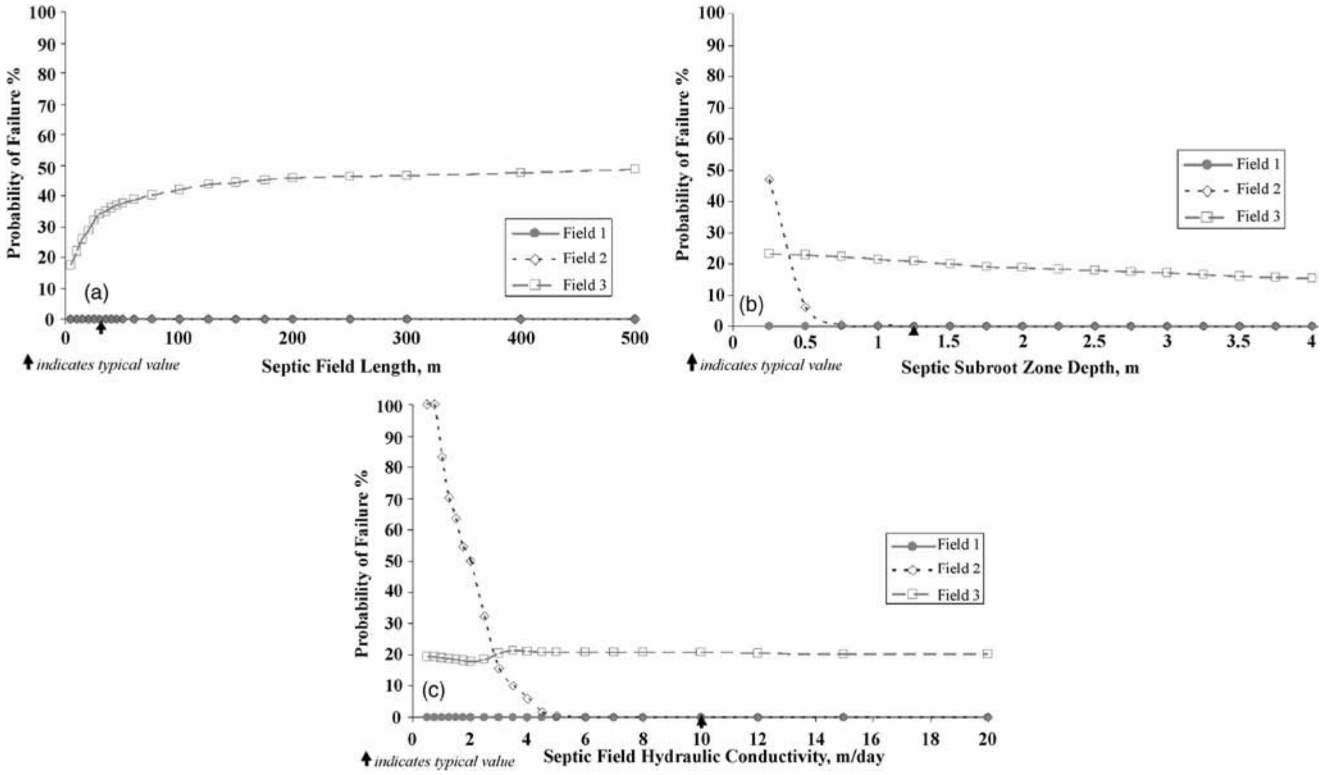

Fig. 5. Probability of failure in Fields 2 and 3 as a consequence of decreasing the conductivity in the septic effluent disposal field. Failure is defined for septic effluent disposal field (Field 2) when the water table exceeds the porous drain pipes and for Field 3 when the water table is within 20 cm of the surface. The water table height in Field 1 is not affected.

should not be surprising, because the variable saturated areas are found in this landscape where subsurface flow collects. The addition of 0.5 cm/d of septic effluent to Field 2 only enhances this phenomenon. Changing the soil depth and conductivity in Field 1 minimally affects the failure rate in the fields downslope [Fields 2 and 3 in Fig. 3(c)]. Low conductivity (<2 m/day) and shallow soil depths (<0.75 m) in Field 1 (upslope) cause a slight decrease in failure rate in Field 3. The reason for this slight decrease is that more surface runoff is generated in Field 1. This runoff will infiltrate in the septic effluent disposal field (without causing the water table to rise above the perforated pipes), and the overall system drains faster due to the high saturated conductivity of the septic field, resulting in a generally lower water table in Field 3.

Plugging of the septic effluent disposal field is examined in Fig. 5(c). Plugging the soil pores with effluent can reduce the conductivity of the soil and increase failure rates (Thom and Keefe 1996). The failure rate in the septic field increases greatly when the conductivity decreases due to plugging of the pores from effluent additions. When the conductivity of the soil above the restricting layer falls below 1 m day^{-1} in the septic field with a slope of 4%, the system failure rate is 100% due to reduced lateral drainage (i.e., $K=K_s \sin \alpha$). Reduced conductivity in the septic field (Field 2) had very little effect on the failure in Field 3, downslope.

Conversely, varying the septic field's length and depth had an effect on failure in Field 3. Longer septic fields (>25 m) increased failure ($>30\%$) in the downslope field, but had no effect on failure in the septic field itself [Fig. 5(a)]. Increasing the depth of the subroot zone soil (or the depth of the soil below the root zone) decreased failure [Fig. 5(b)], below 20% for depths greater than 1.5 m in Field 3 and to 0 for depths of 1.25 m and above in Field 2, the septic field. The failure rate in Field 1 upslope is not affected by varying parameters in the septic field, as is discussed later (Fig. 5).

Fig. 6 shows the failure rate of the downslope Field 3. As expected, the failure rate depends mainly on the ability to carry the imposed flow from Fields 1 and 2. Thus, decreasing soil depth [Fig. 6(b)] and conductivity [Fig. 6(c)] in Field 3 greatly increases the probability of failure. In addition, increasing the field length increases the failure rate due to the greater flux of water flowing through the field when the water table is near the surface (resulting from rainfall in excess of evapotranspiration) [Fig. 6(a)].

Discussion of Model Application

From the preceding analysis, it is obvious that in the undulating Catskills mountain landscape the properties of the upslope field directly affect the hydraulic behavior of the fields downslope. This is especially true for the increasing failure rate for Field 3 (Figs. 4 and 5). The septic field itself is less affected, as is discussed hereafter. The upslope field, however, is not impacted by the downslope field properties simply because the fields are sloped. Water will flow down the hill nearly independently of the rise or fall in the water table. Only in the case of relatively flat fields (i.e., less than 2% as a general rule) can one expect that the flow in the downslope direction might affect the drainage field behavior upslope. For these flatter slopes, the water table gradient is an important factor in calculating the fluxes and would invalidate the model presented in Eqs. (1)–(14). Thus, our results are only valid for undulating landscapes as stated in the objective and cannot be used in areas with little or no slope.

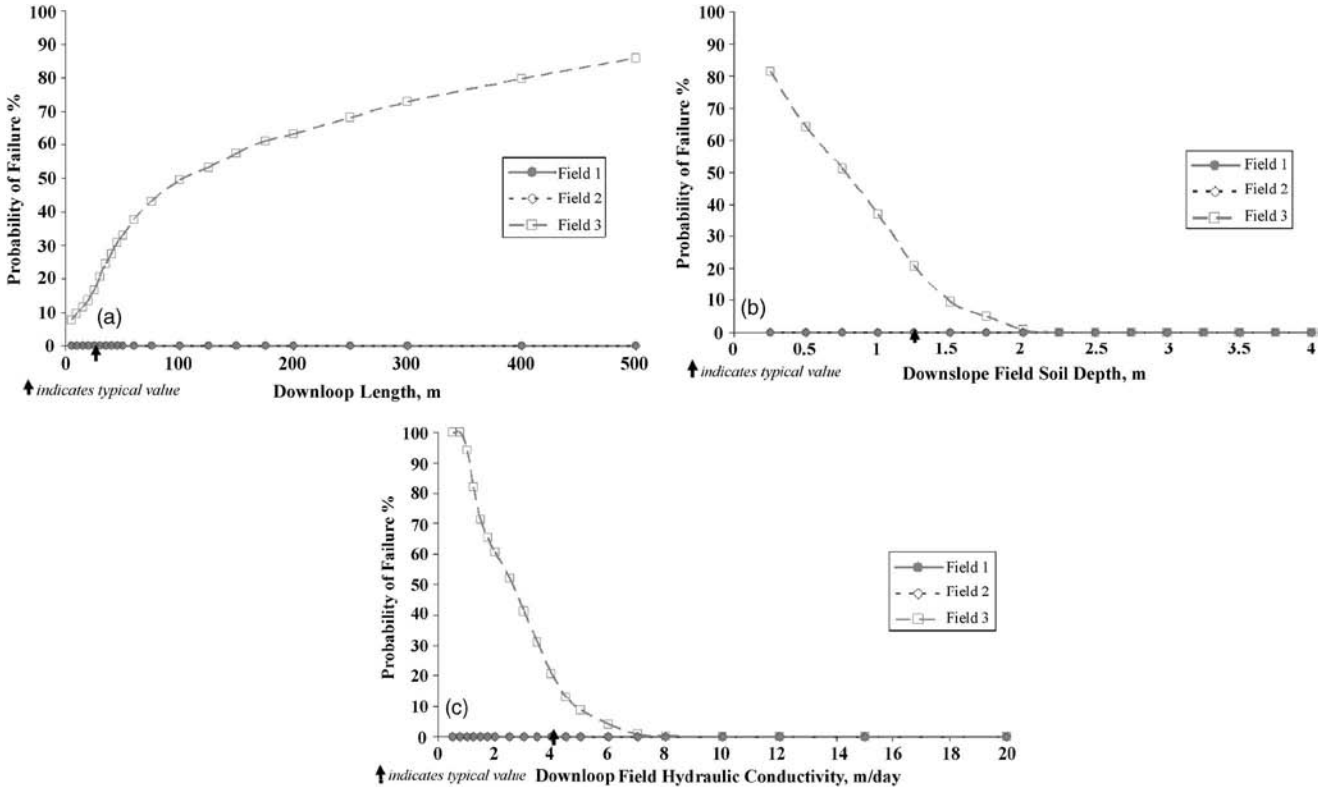

Fig. 6. Probability of failure in Field 3 as a consequence of changing the properties in Field 3. Failure is defined when the water table is within 20 cm of the surface: (a) downslope field length is varied; (b) downslope field subroot zone depth is varied; (c) downslope field saturated hydraulic conductivity is varied. The water table heights in Fields 1 and 2 are not affected.

Varying individual parameters in fields upslope, without also varying parameters in the downslope field, did not effectively decrease the probability of failure in the downslope field. Therefore, throughout the entire year, the watertable in Field 3 surpasses both those in Field 1 and Field 2. Furthermore, during most of the year with the exception of the summer, the water table in Field 2 was lower than Field 1, a consequence of the high conductivity of the imported soil in the septic field. The reason for the reverse trend during extended periods of little or no rain is that the water table above the restricting layer in Field 1 disappeared while there was still a small water table above the restricting layer in Field 2 due to the septic effluent additions. The failure rate in Field 2 increases when the hydraulic conductivity decreases due to clogging. In that case, the water cannot flow out of the septic disposal field fast enough to account for the inflow of the septic tank effluent, and the water table rises. Failure rates are also reported for septic fields in permeable soils with a large depth to restricting layer due to pore plugging (Brown 1992). However, in deep, flat soils overlying aquifers, water moves vertically to the groundwater under a unit hydraulic gradient, with no lateral inflow entering the septic field. In rolling landscapes with a hardpan, the water moves downslope according to the gradient of the slope of the land and there is water entering from upslope.

Another difference is that the whole soil profile is wet on hill slopes, and the pores throughout the profile may clog, while in permeable soils clogging only occurs at the water table interface. Thus in these rolling landscapes, there is more water and a lower hydraulic gradient in the profile than in flat deep soils, and the effect of clogging on the conductivity is noticed at a much earlier stage. Mounded septic systems or shallow adsorption trench fields have been introduced in these rolling landscapes to remedy this problem (Bouma et al. 1975). It should, however, be noted that the failure in the downslope field would be only minimally affected by a mound or trench system, and short-circuiting of the effluent to nearby water bodies could also occur with these systems.

Recommendations

This analysis points out ways that the performance of septic effluent disposal fields can be improved. Failure in Field 3, the downslope field, is strongly dependent on the upslope contributing area (see Figs. 4 and 5) and the properties of the field itself (Fig. 6). Because a large contributing area leads to a high failure rate, reducing the effective area of the contributing land can improve system performance and reduce failure. One commonly accepted practice utilized to reduce the contributing area for an existing system is to install an interceptor or curtain drain upslope from the septic effluent disposal field. This drain prevents upslope water from entering the septic effluent disposal field, and it is already in common practice in New York State (NYS Department of Health 1996). Certain limitations apply to the installation of interceptor or curtain drains and would depend on site conditions in order to minimize the possibility of partially treated wastewater entering the curtain drain and short-circuiting the treatment process. Septic fields should, ideally, be installed where the product of the saturated conductivity in m/day, the sine of the slope (slope in radians), and the soil depth is greater than 0.2 m^2/day for New York State conditions. By varying the values for K_s, α, and d_T in the model simultaneously to achieve the given product limit, a probability of failure less than 10% can be obtained in the septic system. Although this analysis was performed for uniform conditions in each of the fields, the model is applicable to more complex slopes and should be further investigated. Thus, installing septic fields on steeper slopes can improve performance. However, sufficient setback to the stream is required, as water velocity is greater with steeper slopes. In the case of the Cannonsville Reservoir watershed, where depth to the impermeable layer and hydraulic conductivity are difficult to adjust, consideration of the landscape parameters for siting a septic field is important. For example, decreasing the upslope contributing area by installing the septic field further upslope would decrease failure and increase the distance of the septic effluent from a downslope waterbody. From a hydrologic perspective, if septic systems and their leachfields are designed and constructed to conform with recommended state guidelines (NYS Department of Health 1996), it is not clear why the NYC-DEP Rules and Regulations prohibit constructing new systems on slopes greater than 15% if other landscape parameters are duly considered.

Conclusions

A simple water balance model was developed to assess the suitability of shallow, permeable hill slope soils for the siting of septic disposal fields. To track the height of the water table in three "fields" the septic field and the two adjacent fields, one upslope of the septic field and one downslope, the model uses easily accessible data, including soil, weather, and effluent volumes typical for the Cannonsville, a New York City drinking water basin. Weather data collected in the watershed from 1996 to 2000 was used to calculate the soil moisture content of the profile, and ultimately the flow regime (saturated or unsaturated) governing the flux of water and effluent from the soil. The addition of a lateral flow function, which fluctuated with the slope of the land, was imperative to correctly capture the soil moisture content, and hence the water table height above the restricting layer. The model, as tested here, appears appropriate for assessing hydrologic conditions and septic system performance in a wide variety of situations. For existing septic systems, this model can be useful for predicting the probability of failure given various hydrologic and field parameters and indicate the parameters which, if adjusted, would decrease this failure. Furthermore, analysis of the model showed that saturated hydraulic conductivity, depth to the impermeable layer, and slope of the drain field are critical parameters to assess in the design of these systems. The integration of these critical parameters indicates the extent of failure for a septic system. Ultimately, this model can be utilized to determine the optimum combination of critical parameters for a potential septic system site given the appropriate hydrological data, septic loading rates, and landscape parameters in order to minimize failure and ensure an effectively operating septic system, which conforms to given state guidelines.

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