Design and Performance of Onsite Wastewater Soil Absorption Systems

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TABLE OF CONTENTS

Page No.

List of Figures ii
List of Tables ii
1. Abstract 1
2. Introduction 1
3. Soil Absorption System Features and Design Basis 5
   3.1. Features and Design of Modern WSAS 5
   3.2. Modifications to Classic System Designs 11
   3.3. Alternative Unit Operations to Classic System Designs 13
4. Performance Capabilities, Predictability, and Reliability 14
   4.1. General Performance Capabilities of WSAS 14
   4.2. WSAS Treatment Potential for Key Pollutant Groups 17
      4.2.1. Organics and Suspended Solids 17
      4.2.2. Nutrients 17
      4.2.3. Pathogens 18
   4.3. Factors and Processes affecting Performance 19
      4.3.1. Soil and Site Conditions 19
      4.3.2. WSAS Design Features 23
      4.3.3. WSAS Construction and Operation and Maintenance 26
   4.4. Modeling WSAS Hydraulic and Purification Performance 27
5. Risk Assessment/Management Applied to Wastewater Soil Absorption Systems 29
   5.1. Risk Assessment and Risk Management Framework 29
      5.1.1. Risk Assessment 29
      5.1.2. Risk Management 29
   5.2. RA/RM for Onsite Wastewater Soil Absorption Systems 30
6. Critical Questions and Research Needs 33
   6.1. Questions and Areas of Research Need 33
   6.2. Prioritization of Research Needs 35
7. Conclusions 35
8. Acknowledgments 41
9. References Cited 41
10. Appendix – Acronyms, Abbreviations, and Symbols 48

LIST OF FIGURES

Page No.

Fig. 1. Schematic of a modern wastewater soil absorption system and the engineering and design vs. site evaluation facets of system implementation....3
Fig. 2. Illustration of wastewater soil absorption system treatment processes....3
Fig. 3. Conceptual framework for risk assessment/management of wastewater soil absorption systems....4
Fig. 4. Examples of soil absorption unit design approaches, including: (a) conventional trench excavation, (b) narrow trench excavation, (c) deep textile-lined narrow trench, (d) gravel-filled trench with geotextile overlay and 10-cm diameter STE delivery piping compared to a gravel-free chamber unit, (e) gravel-free chamber unit....8
Fig. 5. Examples of effluent delivery methods for delivery of wastewater effluent into the soil absorption unit: (a) STE baffle and gravity outlet, (b) 10-cm diameter perforated drain tile, (c) drop-box serial distribution for sloping sites, and (d) hydrosplitter to equalize flow between trenches....8
Fig. 6. Examples of wastewater source modifications: (a) 3-L volume flush toilet, (b) compost toilet, (c) graywater recycle unit, and (d) point-of-use bag filter for laundry discharge....11
Fig. 7. Examples of alternative unit operations including: (a) effluent biofilter unit, (b) in-tank aeration unit, (c) rotating biological contactor, (d) sand filter, (e) foam filter, and (f) drip irrigation line....14
Fig. 8. System hydraulic function versus operational age and installation period....16
Fig. 9. Time-dependent infiltration rate changes during wastewater application related to the initial saturated hydraulic conductivity of the media for clean water (from Jenssen, 1986)....21
Fig. 10. Ground water mounding under WSAS as a function of infiltration rate, aquifer depth and hydraulic conductivity, and distance to a hydraulic barrier (after Jenssen and Bromssen, 1985)....22
Fig. 11. Illustration of infiltration rate loss in a standard gravel-filled trench based on the cumulative mass density loading of total BOD and suspended solids (kg m^{-2}) at different hydraulic loading rates and effluent compositions (after Siegrist 1987; Siegrist and Boyle, 1987)....23
Fig. 12. Purification efficiency as affected by reaction rate and operating conditions which is turn impact hydraulic retention time (after Ausland, 1998)....25

LIST OF TABLES

Page No.

Table 1. Physical and operational features of historical, current, and emerging wastewater soil absorption system designs....6
Table 2. Wastewater COC's and representative concentrations in effluents applied to WSAS and percolates reaching ground water....7
Table 3. Design and environmental conditions affecting WSAS performance....20
Table 4. Mathematical models and decision-support tools for design and performance of onsite wastewater soil absorption systems....28
Table 5. Example scenarios for wastewater soil absorption systems that pose apparent risks to human health and environmental quality and example risk management options....31
Table 6. Example risk management strategies and options for wastewater soil absorption systems at the site-scale and watershed scales....32
Table 7. Research questions for wastewater soil absorption systems....36
Table 8. Prioritization of research questions into ranked research needs....40

Design and Performance of Onsite Wastewater Soil Absorption Systems

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1. Abstract

The primary system for onsite and decentralized wastewater treatment in the U.S. includes septic tank pretreatment followed by subsurface infiltration and percolation through the vadose zone prior to recharge of the underlying ground water. These wastewater soil absorption systems (WSAS) have the potential to achieve high treatment efficiencies over a long service life at low cost, and be protective of public health and environmental quality. Favorable results from lab and field studies as well as an absence of documented adverse effects suggest that system design and performance are generally satisfactory. However, the understanding and predictability of performance as a function of design, installation/operation, and environmental factors, as well as the risk of inadequate function and its effects, have not been fully elucidated. This has been due to the complex and dynamic relationships between hydraulic and purification processes and the factors that control their behaviors. As a result, the current state-of-knowledge and standard-of-practice have gaps and shortcomings that can preclude rational system design to predictably and reliably achieve specific performance goals. Moreover, the quantitative analysis of long-term treatment efficacy on a site-scale up to watershed scale is difficult, as is any formal assessment of risks and selection of appropriate management actions. This white paper describes the process function and performance of WSAS. The system performance capabilities and predictability as well as reasonably conceivable system dysfunctions are described within a risk assessment and management framework. Issues applicable to the single-site scale and to the multiple-site to watershed scales are addressed. Based on an analysis of the current state-of-knowledge, critical research needs are identified and prioritized. As described herein, critical questions and current gaps in knowledge generally relate to the absence of fundamental process understanding that enables system performance relationships to be quantified and modeled for predictive purposes. High and very high priority research needs include those that support: (1) fundamental understanding of clogging zone genesis and unsaturated zone dynamics and their effects on treatment efficiency, particularly for pathogens, (2) development of modeling tools for predicting WSAS function and performance as affected by design and environmental conditions, (3) identification of indicators of performance and methods of cost-effective monitoring, and (4) development of valid accelerated testing methods for evaluating long-term WSAS performance.

2. Introduction

Wastewater infrastructure in the U.S. includes a continuum of technologies designed for scales of application that span from small decentralized systems serving individual homes in rural and suburban areas, to large centralized systems serving municipalities in densely populated urban areas. In the past, the decentralized or onsite systems were viewed by some as a means of providing temporary service until city sewers and a centralized treatment plant became available to provide permanent service. Early versions of onsite wastewater systems (e.g., pit privy, cesspool) were often designed with simple and short-term goals of waste disposal to prevent direct human contact and to achieve basic public health and environmental protection.

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In the early 1900's, some system designs evolved to include raw wastewater pretreatment in a tank-based unit (e.g., septic tank) followed by disposal through a soil drainfield, and extension bulletins and guidance materials began to appear. As modern appliances became more commonplace, high water-use plumbing fixtures resulted in increased wastewater flows and a need for more careful siting and design of onsite wastewater soil absorption systems. For many designers and regulatory officials, the systems were still often viewed temporary with relatively simple waste disposal goals. During the 1990's the rapid movement toward centralization of wastewater treatment faded for a number of reasons, including the end of construction grants funding for treatment plants and a realization that large centralized solutions were not appropriate for all situations. Continuing to evolve, classic and alternative WSAS have been increasingly viewed as *treatment systems* and they have been designed and implemented to achieve purification as well as disposal, and even considered for beneficial reuse. Recently, increasing concerns over ground water quality and the effects of hazardous chemicals and waste pollutants have elevated the attention given to proper design and performance of WSAS. Today, nearly 25% of the U.S. population is served by onsite and decentralized wastewater systems and approximately one-third of new development is supported by such systems (USEPA, 1997). This amounts to roughly 25 million existing systems with 0.2 million new systems being installed each year. These onsite systems are now viewed as a necessary and permanent component of sustainable wastewater infrastructure in the U.S. and abroad.

The most common WSAS includes intermittent delivery (by gravity or pressurized dosing) of primary treated wastewater into the subsurface with infiltration and percolation through the vadose zone and into the underlying ground water (Fig. 1). Successful application of WSAS is based on engineering design that is compatible with the environmental conditions as determined through a site evaluation (Fig. 1). In properly implemented WSAS, advanced treatment is expected and can be achieved for many wastewater constituents of concern (COC's) through removal (e.g., filtration of suspended solids or sorption of phosphorus), transformation (e.g., nitrification of ammonium or biodegradation or organic matter), and destruction processes (e.g., die-off of bacteria or inactivation of virus) (Fig. 2). For the purposes of this discussion, the boundaries of the *WSAS treatment system* include the inlet to the soil absorption unit through the lower limit of the underlying vadose zone (see Figs. 1 and 2). In these WSAS, the conditions imposed by the WSAS process design (e.g., applied effluent quality and hydraulic loading rate) in a given environmental setting (e.g., soil type, moisture and temperature) must be such that key treatment processes occur at a rate and to an extent such that advanced treatment is reliably achieved before ground water recharge occurs (see Fig. 1). This is critical since the percolate released from most WSAS enters the underlying ground water, which can migrate under natural gradients toward points of exposure for receptors of concern (e.g., humans and drinking water supplies). Depending on local and regional conditions, ground water transport/fate processes may or may not reduce percolate COC concentrations, which would be of concern if exposure occurred at the point of percolate entry to the ground water, to lower levels that are not of concern at a remote point of exposure (Fig. 3).

In contrast to the modern WSAS simply illustrated in Figure 1, the large population of onsite systems in the U.S. today is extremely heterogeneous, including an array of old and new system designs, located in varied site conditions with different environmental sensitivities, and used to treat wastewaters from residential, commercial, and institutional sources (Table 1). Moreover, this population of systems includes those that are properly designed, installed and operated as well as those that are poorly designed, incorrectly sited, and/or improperly operated and maintained. Thus, characterization of performance capability and reliability for modern WSAS (e.g., Fig. 1) that are properly implemented in a given application must not be skewed based on the performance observed for older systems (e.g., disposal-based designs) and/or inappropriate applications (e.g., poorly sited systems).

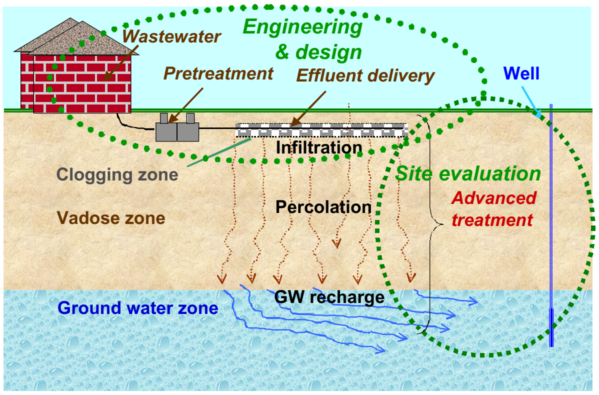

Fig. 1. Schematic of a modern wastewater soil absorption system and the engineering and design vs. site evaluation facets of system implementation.

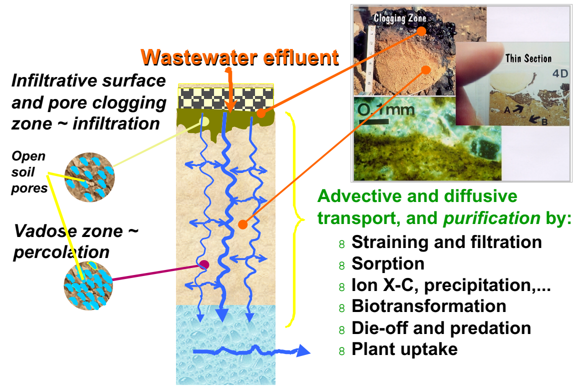

Fig. 2. Illustration of wastewater soil absorption system treatment processes.

For example, a very old system (e.g., 50-yr. old cesspool) might function effectively for hydraulics and disposal, yet accomplish limited purification, and thus its performance with respect to modern goals of treatment would be viewed as inadequate. This is in contrast to more modern systems designed to exploit physical, chemical, and biological processes to achieve highly efficient hydraulic and purification performance (e.g., 5-yr. old WSAS with pressure dosing of septic tank effluent into a network of shallow (e.g., 30 to 60 cm), narrow (e.g., 15 to 30 cm) trenches). In this paper, the emphasis will be on modern WSAS that have been designed, installed, and operated since about 1980 when contemporary understanding of onsite and decentralized systems was well documented and information was widely available (e.g., see USEPA, 1978; 1980).

Wastewater poses inherent risks due to its microbial and chemical constituents. The challenge with its management is to assess the magnitude of the risks in a given situation and decide on the most appropriate method to manage those risks (Fig. 3). For example, pathogenic bacteria, virus, and protozoa are present in wastewater, and disease could result if they are not removed or inactivated before an effluent reaches a receiving environment where humans can contact and ingest the water (e.g., drinking water, bathing beaches, shellfish beds). Also, if excessive levels of nitrogen and phosphorus in wastewater are input to sensitive surface waters (e.g., pristine lakes, estuaries), this could result in undesirable ecosystem changes (e.g., increased productivity and eutrophication). While simply stated, risk-based design and application of onsite WSAS is quite difficult to implement. For wastewater treatment, one could state the ultimate goal as being WSAS design and implementation so that (1) there is no infectious disease attributable to an onsite wastewater system, and (2) there is no measurable change in an ecosystem attributable to wastewater system inputs. Clearly, in a given setting, an onsite system that provides no treatment at all may present the highest risk, while increasing levels of reliable treatment effectiveness yield reduced levels of risk. However, since risk management requires consideration of nontechnical issues, such as socioeconomic factors, the most advanced treatment system will generally not be the best overall risk management solution.

Older systems that were designed and implemented to achieve disposal may represent an unacceptable risk to public health and environmental quality and need upgrading or replacement. A clear example of such a situation would include cesspools constructed in the ground water and with limited travel distances to drinking water supplies or sensitive surface waters. Other older systems are not so easily identified as inadequate and in need of upgrade or replacement. Modern onsite and decentralized systems are increasingly being designed and implemented as permanent and sustainable solutions for wastewater *treatment* rather than just disposal. In this context, *treatment* embodies goals associated with effective hydraulic and purification performance that can be sustained over a long service life at an affordable cost.

If these goals are sought and achieved, onsite systems can effectively manage public health and environmental quality risks that are inherent with microbial and chemical constituents normally found in domestic wastewater.

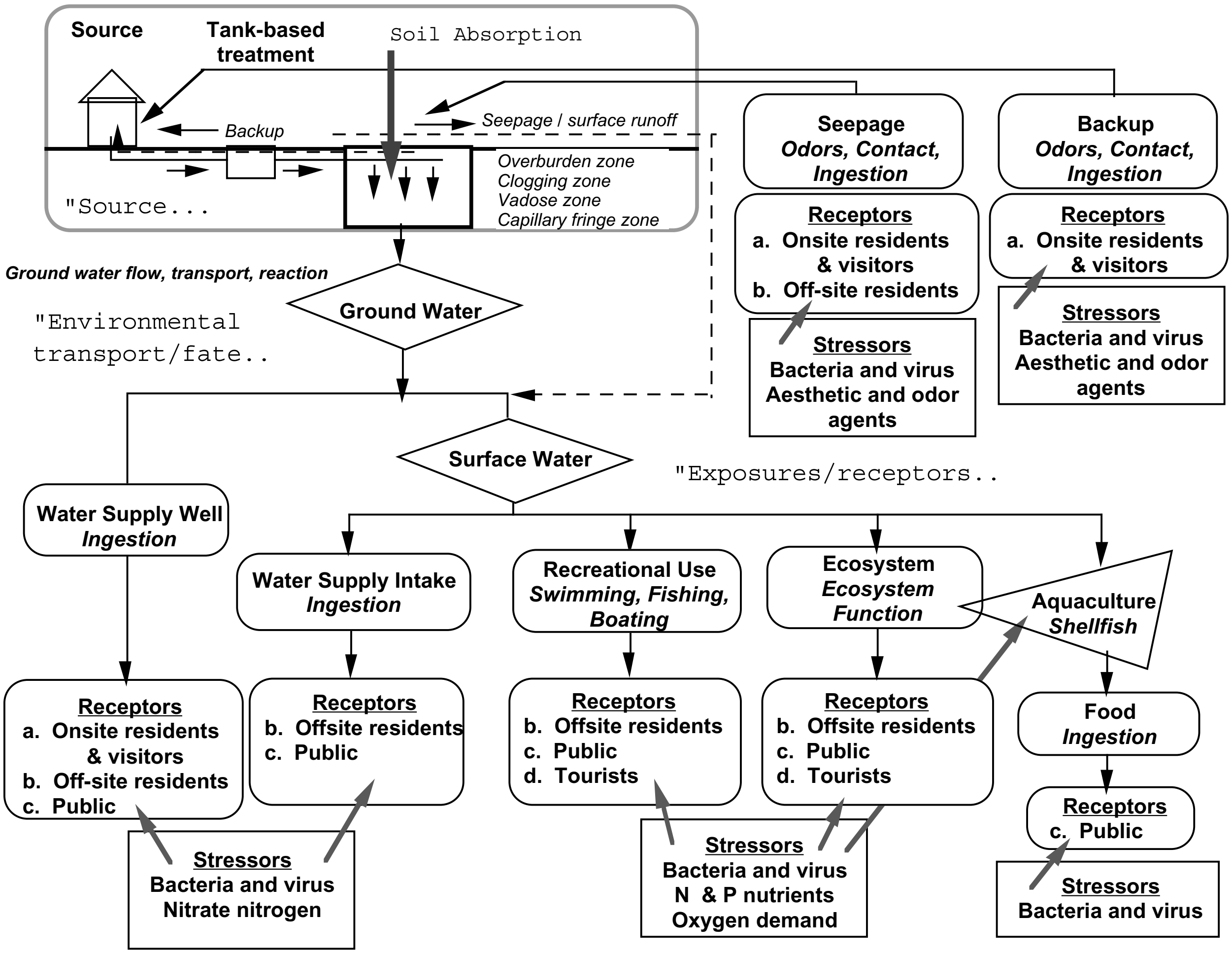

Fig. 3. Conceptual framework for risk assessment/management of wastewater soil absorption systems.

The design of wastewater systems for risk management necessarily requires the implicit or explicit setting of treatment goals. Only recently have attempts been made to explicitly establish performance goals or standards for WSAS (e.g., Otis and Anderson, 1994; Hoover et al., 1998b), in large part because this has been difficult for soil absorption systems. Explicitly establishing treatment goals and assessing their achievement requires that specific COC's are identified and the assessment methods are clearly defined. For a tank-based unit operation, it is straightforward to identify a common characteristic such as BOD_5 as a COC and to set the treatment goal as a certain average effluent concentration (e.g., 30 mg/L) and/or a % reduction in the influent concentration (e.g., 90%). The performance assessment could be made using 24-hr flow composited samples collected once each week with statistical analysis of the resulting dataset on a quarterly or annual basis. For WSAS, this is much more complicated based on both the variety of COC's that might be present (e.g., organics, nutrients, pathogens) in a given environmental setting and the absence of an "end-of-pipe" point of assessment. For example, one could assign the equivalent end-of-pipe assessment point to any one of the following: (1) soil solution in the lower limit of the vadose zone under the infiltration system under the seasonally highest water table elevation, (2) ground water at the downgradient edge of the footprint of the infiltration unit, (3) the ground water at the property boundary, or (4) the water at some proximal receptor that would be sensitive to potential wastewater system inputs (e.g., drinking water, shellfish waters). As of this writing, standardized performance goals have been advocated (e.g., Otis and Anderson, 1994; Hoover et al., 1998a), but there appears to be no consensus as to the COC's, the performance to be achieved within a prescribed space-time domain, or the methods to be used to measure and assess compliance. In this paper, the primary COC's are defined to include measures of oxygen consuming materials (e.g., BOD_5 and COD), nutrients (e.g., N and P), and human pathogens (e.g., bacteria and virus) based on their prevalence and potential adverse effects on human health and environmental quality. The primary treatment unit boundaries for a WSAS are defined to include the influent from a tank-based treatment unit (e.g., septic tank) through infiltration and percolation of the vadose zone and capillary fringe before discharge to a receiving ground water environment (Fig. 3). However, the method of performance assessment is not defined as it is application specific and many factors need to be considered such as system type, size, and the sensitivity of the primary receiving environments (e.g., ground water) and secondary recipients (e.g., surface waters).

3. Soil Absorption System Features and Design Basis

3.1. Features and Design of Modern WSAS

While old and new WSAS vary widely in their design and implementation (see Table 1), the vast majority of systems are based on discharge of partially treated wastewater effluent to subsurface soils with recharge to ground water underlying the site. The classic onsite system of modern design involves a wastewater source (e.g., dwelling unit), tank-based treatment unit (e.g., septic tank), and an infiltration unit (e.g., subsurface trench or bed) (Fig. 1). In this system type, water use from all fixtures and activities generates a combined raw sewage (solid plus liquid wastes) which flows into a septic tank buried outside but adjacent to the home or establishment. The principal treatment processes in a septic tank include sedimentation, flotation, and some anaerobic digestion. Septic tank effluent (STE) still contains high concentrations of organic matter, total suspended solids (SS), nutrients, and microorganisms and is not suitable for discharge to a receiving environment without further treatment (see Table 2). Requisite further treatment is achieved by discharging STE into a subsurface trench or bed filled with gravel aggregate or outfitted with a chamber, from which infiltration and percolation occur through an underlying unsaturated zone with recharge to ground water under the site (see Figs. 4 and 5). When a partially treated effluent such as STE, is applied to soil, infiltration and percolation through the unsaturated porous media involve a complex set of hydraulic and purification processes that can interact to reliably and sustainably achieve advanced treatment efficiencies (Table 2). These hydraulic and purification processes interact in a dynamic manner, evolving as a WSAS matures from startup through the first year(s) of operation.

Design of WSAS has historically been accomplished through a series of steps such as the following:

- Estimate the wastewater flow and composition with an implicit or explicit factor of safety,
- Characterize the site for landscape and land use features,
- Determine the subsurface lithology and hydraulic properties, and identify any limiting features,
- Select a design hydraulic loading rate, often based on a long-term acceptance rate for effluent,
- Specify geometry and placement of the infiltrative surface and its interface features,
- Select and size the pretreatment unit and the effluent delivery and distribution method,
- Determine what modifications, if any, are needed and appropriate for the site, and
- Select process controls and monitoring devices.

Table 1. Physical and operational features of historical, current, and emerging wastewater soil absorption system designs.[1]

Period of use	System type or operational feature	Motivation	Description of representative system features
1. Historical system designs	A. Cesspool	Disposal	Open or lined (e.g., brick or block) pit into which raw wastewater is discharged. Solids are retained in the pit while effluent infiltrates into the surrounding soil for disposal though some treatment can occur.
	B. Seepage pit	Disposal, some treatment	Open or lined (e.g., brick or block) pit into which pretreated wastewater is discharged. Effluent infiltrates into the surrounding soil for disposal though some treatment can occur.
	C. Leachfield	Disposal, more treatment	Network of trenches or beds filled with gravel or aggregate for disposal of pretreated wastewater by infiltration and percolation.
2. Current common system designs	A. Trench / bed WSAS	Disposal and treatment on favorable sites	Engineered network of trenches or beds filled with gravel or outfitted with chambers from which wastewater effluent (often from a septic tank [2]) infiltrates and percolates through 1 to 5 ft. or more of unsaturated soil before recharging ground water under the site.
	B. Shallow LPP WSAS	Disposal and treatment on difficult sites	Shallow, narrow trenches used for wastewater infiltration by intermittent delivery of wastewater effluent. Originally designed for sites with shallow, slowly permeable soils and seasonally high water table conditions.
	C. At-grade WSAS	Disposal and treatment on difficult sites	Trench or bed WSAS designed with the infiltration surface placed at the original ground level. Designed for sites with shallow depth to limiting conditions such as seasonally high water table or bedrock.
	D. Mound WSAS	Disposal and treatment on difficult sites	Trench or bed WSAS designed with the infiltration surface placed within a bed of imported sand fill above the original ground surface by 1 to 2 ft. Designed for sites with very shallow depth to limiting conditions such as seasonally high water table or bedrock.
2A. Current common installation or operational variants	A. Drainage	Increase vadose zone depth	Use of dewatering trenches or drains to lower the permanent or seasonal water table such that an adequate depth of unsaturated soil is maintained between the infiltrative surface.
	B. Over-excavation	Reduce particle sizes, increase media contact	Construction technique used wherein naturally occurring bedrock is excavated and crushed onsite and then placed back into the excavation. This creates a coarse grained fill into which a trench or bed WSAS can be installed.
	C. Dosing application	Cyclic loading, better distribution	Intermittent application of effluent to any WSAS with delivery in large draintile or small diameter pressure pipe.
	D. Pressurized dosing	Cyclic loading, uniform distribut.	Operational method of intermittent application of effluent into small diameter pressurized pipe to achieve more uniform distribution through the WSAS.
3. Emerging designs and operational variants	A. In-tank STE filters	SS removal	Filter cages installed into the effluent baffle from a treatment tank to capture suspended solids.
	B. Timed-pressure appl.	Cyclic loading, equalization	Design to include a pump vault and high/low switching gear with hourly bursts of STE discharged to a WSAS. Over a narrow range of liquid levels, the septic tank can provide some equalization capacity.
	C. Drip application	Treatment and reuse	Method of soil application where STE is further treated by optional methods before delivery to the shallow soil zone by timed pump application and drip emitter lines.
	D. Interm. sand filters	Adv. treatment	Design with single pass or recirculation through a 2 to 4 ft. packed bed of engineered sand media.
	E. Advanced treatment units (ATU's)	Adv. treatment	Tank based systems using biological treatment in suspended growth or packed bed systems, possibly incorporating biofilm supports of foam, textiles, or other materials.
	F. NO_3^- removal	Adv. treatment	Recirculation of STE through a packed bed and return to the influent end of the septic tank for nitrification-denitrification.
	G. UV irradiation	Disinfection	After advanced treatment, irradiation with UV light to kill/inactive pathogenic organisms in the effluent.

1 The information is provided to represent typical characteristics for residential systems and it is recognized that all known or possible system designs or operational strategies are not included.
2 In some locations, aerobic treatment units (e.g., extended aeration package plants) are conventionally used for pretreatment prior to wastewater application to soil.

Table 2. Wastewater COC's and representative concentrations in effluents applied to WSAS and percolates reaching ground water.

Constituents of concern (examples)	Example direct or indirect measures (Units) *Degree of explicit consideration in design or assessment*	Basis for concern over wastewater constituent	Relative degree of concern over treatment effectiveness of WSAS	Tank-based treatment unit effluent concentrations					WSAS percolate reaching ground water at 3 to 5 ft. depth (% reduction of effluent applied)
				Domestic septic tank effluent [1]	Domestic septic tank effluent with N-removal recycle [2]	Aerobic unit effluent	Sand filter effluent	Foam or textile filter effluent	
Oxygen demanding substances	BOD_5 (mg/L) *Common* [3]	(1) Create anoxic or anaerobic conditions and (2) stimulate clogging development	Low	140 to 200	80 to 120	5 to 50	2 to 15	5 to 15	>90%
Particulate solids	TSS (mg/L) *Common*	(1) Pore plugging and accelerated soil clogging	Low	50 to 100	50-80	5 to 100	5 to 20	5 to 10	>90%
Nitrogen	Total N (mg-N/L) *Common*	(1) Contributes to oxygen demand, (2) toxic via drinking water ingestion by sensitive receptors, (3) upset productivity in receiving waters.	High	40 to 100	10 to 30	25 to 60	10 to 50	30 to 60	10 to 20%
Phosphorus	Total P (mg-P/L) *Not common*	(1) causes increased productivity in surface waters.	Low	5 to 15	5 to 15	4 to 10	<1 to 10[4]	5 to 15[4]	100 to 0% [4]; highly variable due to soil's P sorption capacity
Bacteria (e.g., *Clostridium perfringens, Pseudomonas aeruginosa, Salmonella, Shigella*)	Fecal coli. (org./100 mL) *Common*	(1) infectious disease hazard to sensitive receptors by drinking water ingestion or contact with untreated seepage or via recreational water exposures.	Medium to high	10^6 to 10^8	10^6 to 10^8	10^3 to 10^4	10^1 to 10^3	10^1 to 10^3	>99.99%
Virus (e.g., enteric virus such as hepatitis, polio, echo, and coxsackie; coliphage)	Specific virus (pfu/mL) *Not common*	(1) infectious disease hazard to sensitive receptors by drinking water ingestion or contact with untreated seepage or via recreational water exposures.	High	0 to 10^5 (episodically present at high levels)	0 to 10^5 (episodically present at high levels)	0 to 10^5 (episodically present at high levels)	0 to 10^5 (episodically present at high levels)	0 to 10^5 (episodically present at high levels)	>99.9%
Organic chemicals (VOCs, endocrine disruptors)	Specific organics or total VOCs (ug/L) *Not common*	(1) potential carcinogens to humans by ingestion in drinking water or vapor inhalation during showering	Low at present	0 to trace levels (?)	0 to trace levels (?)	0 to trace levels (?)	0 to trace levels (?)	0 to trace levels (?)	>99%
Heavy metals (e.g., Pb, Cu, Ag, Hg)	Individual metals (ug/L) *Not common*	(1) potential toxicants to humans by ingestion in drinking water or (2) to ecosystem biota	Low at present	0 to trace levels	0 to trace levels	0 to trace levels	0 to trace levels	0 to trace levels	>99%

[1] Note: concentrations given are for single family dwelling units. Multiple family units are probably quite similar. However, concentrations in restaurant STE are markedly higher particularly in BOD_5, COD and suspended solids (see Siegrist et al., 1985). Concentrations in graywater STE are noticeable lower in total nitrogen (see Siegrist and Boyle, 1982).

[2] N-removal accomplished by recycling STE through a packed bed for nitrification with discharge into the influent end of the septic tank for denitrification.

[3] None indicates characterization and monitoring not done and design basis limited with respect to these COC's.

[4] P-removal by adsorption/precipitation is highly dependent on media sorption capacity and P loading rates and time of operation.

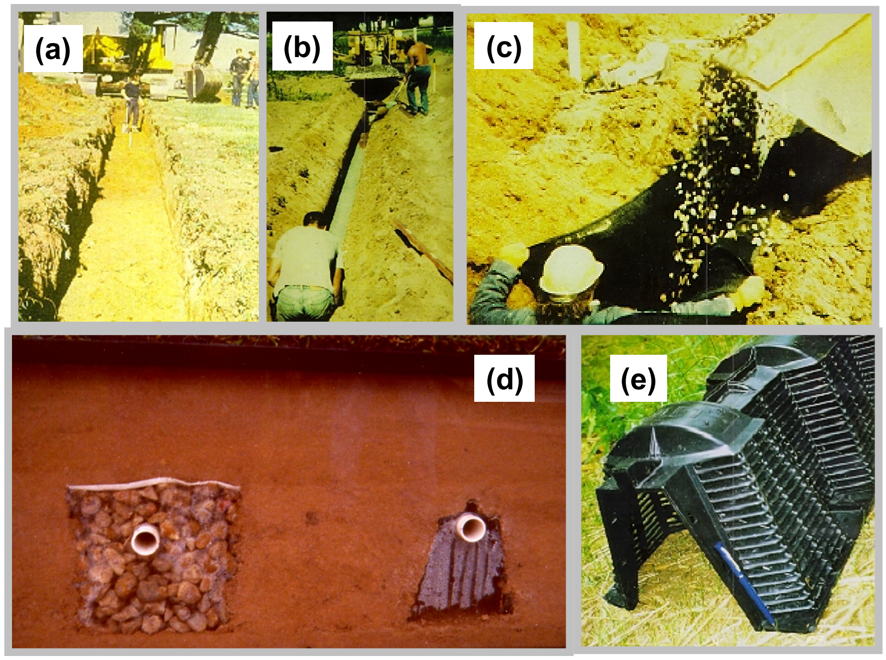

Fig. 4. Examples of soil absorption unit design approaches, including: (a) conventional trench excavation, (b) narrow trench excavation, (c) deep textile-lined narrow trench, (d) gravel-filled trench with geotextile overlay and 10-cm diameter STE delivery piping compared to a gravel-free chamber unit, (e) gravel-free chamber unit.

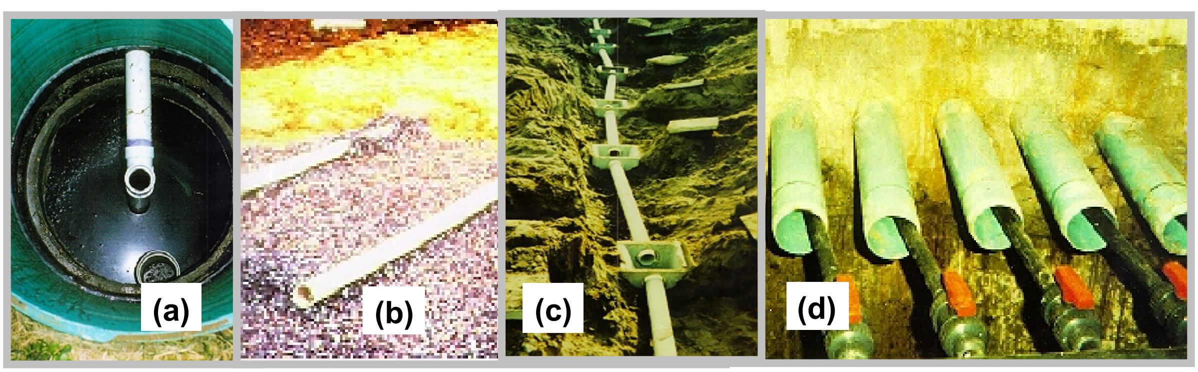

Fig. 5. Examples of effluent delivery methods for delivery of wastewater effluent into the soil absorption unit: (a) STE baffle and gravity outlet, (b) 10-cm diameter perforated drain tile, (c) drop-box serial distribution for sloping sites, and (d) hydrosplitter to equalize flow between trenches.

The design of WSAS has normally been completed with an over-riding conservatism in most all steps of the process, for example during selection of the (1) design flow, (2) septic tank size, and (3) application rate to the soil infiltrative surface (IS). The experiences and preferences of local designers and contractors, as well as the availability of materials and equipment, that lead to the lowest system costs often determine the WSAS designs that are most commonly used. For single-family home and other small WSAS, the design practices are often prescribed in state or local codes (e.g., Docken and Burkes, 1994; Briggs and Barranco, 1994) which can vary widely from state to state and even county to county within a given state. The codes themselves have evolved from local practices and perceptions, sometimes accounting for local conditions (e.g., topography, climate), but often not based on any fundamental understanding or even objective technical data. Recognizing the great range in actual past and current practices, the following remarks are made to illustrate the type of practices used for a classic WSAS serving a single-family dwelling unit.

Design flows are commonly calculated for a single-family home based on a per capita flow and a residency estimate (USEPA, 1980a; Crites and Tchobanoglous, 1998). Flow estimates for commercial and institutional sources are based on occupancy and/or event/activity water-use and are much more difficult to estimate accurately due to highly uncertain practices (Siegrist et al., 1985a). For a single-family dwelling unit with four bedrooms, the design flow might be estimated at 2.27 m^3/d (600 gallons per day, gpd) (assuming all four bedrooms are occupied by two persons each of whom produces 280 L per day (Lpd) of wastewater (75 gal per capita per day, gpcd). This represents an implicit factor of safety of over 500% compared to an average occupancy of 2.1 persons per home and average per capita flow of 170 Lpd (45 gpcd) (USEPA, 1978; 1980). This large factor of safety may be appropriate for one single dwelling unit to ensure that the actual flow generated at any individual dwelling within a large population of dwellings does not exceed the design flow. However, for a cluster of dwellings (e.g., five or more homes on a clustered system), the design flow can be reduced toward the average since the clustering attenuates the actual flow variations from home to home. For clusters of 5 or more dwelling units, the daily design flow can be based on average conditions with an explicit factor of safety (e.g., 1.5 to 2.0) applied to the base flow.

Septic tanks are normally sized based on the design flow and 2/3 of the tank volume set aside for sludge and scum accumulation and a 24-hr hydraulic detention time in the remaining 1/3 volume. This effectively yields a total tank volume equal to 3 times the daily flow volume (Baumann et al., 1978; USEPA, 1980a). The septic tank sizing and design features can affect the average STE output rate and quality as well as the raw wastewater source (see Tables 1 and 2). Baffles are provided on the inlet and outlet of a septic tank (see Fig. 5) to yield quiescent conditions within the tank and limit the disruption and re-entrainment of sludge and scum in the wastewater passing through the tank, thereby minimizing suspended solids concentrations in the STE. Sludge and scum accumulate over time in a septic tank and these solids must periodically be pumped out and properly managed (USEPA, 1995). The needed frequency of pumping and composition of the removed solids, referred to as septage, has been related to the type of usage (e.g., with garbage disposals) and environmental conditions (e.g., temperature)(USEPA, 1980a,b; 1995; Bounds, 1995a,b).

The soil absorption unit size is determined by selecting (1) a specific infiltrative surface geometry (e.g., sidewall vs. bottom area) and placement in the soil profile (e.g., *in situ* deep, *in situ* shallow, at grade, or mounded in fill), (2) infiltrative surface character (e.g., gravel-laden or gravel-free chamber units, and (3) estimating the steady-state hydraulic capacity (e.g., cm/d) of the IS once a system is fully mature and soil clogging has approached its maximum (see Fig. 5). While bed geometries permit more efficient use of landscape area, with increasing IS area per unit length of system, beds can experience diminished performance due to construction damage, high overburden pressures and gravel embedment, gas entrapment and anaerobiosis due to inhibited O_2 transfer, and potentially excessive ground water mounding and reduced unsaturated zone depth (Siegrist et al., 1984; 1986; Mahuta and Boyle, 1991). To mitigate the negative effects of beds, trench geometry's with shallow placement have been advocated to maximize IS area and exploit the most biogeochemically active zone of the soil profile. The required gross area of IS is based on the design flow divided by a long-term acceptance rate (LTAR) for the IS expressed in volume per area per time (e.g., 1 cm^3/cm^2/d = 1 cm/d = 0.245 gpd/ft^2). This gross IS area may be increased by a factor of 1.5 to allow for extended resting (e.g., 6 mon.) of 1/3 of the absorption system to retard soil clogging development. The gross IS required is then converted to a length of trench of a prescribed width (e.g., 90 cm or 3 ft.) which then must be laid out on the landscape. Trench separation is prescribed (e.g., 1.8 m or 6 ft.) to enable a platform for construction equipment during installation. Modern installation methods can use specialized equipment (e.g., continuous trenchers) for which trench separation can be quite low based on equipment constraints alone.

For most systems, delivery and application of the STE to the absorption area is based on wastewater generation in the dwelling unit or establishment with gravity flow from the septic tank designed to be distributed to all of the operational absorption trenches or bed units. Attempts to distribute the flow equally between trenches or areas of a bed using distribution boxes and 10-cm (4-in) diameter perforated drain pipe are commonly made, but have been shown to be ineffective (Otis et al., 1978) (see Fig. 5). As described below, this has led to modifications in system design that incorporate dosing into larger gravity piping or dosing into small pressurized piping for more uniform delivery. For some systems, serial distribution is used whereby a portion of a system is hydraulically overloaded during system startup, but as clogging evolves, additional trenches are loaded based on overflow from an upslope trench (Otis et al., 1978).

The total infiltration area required in a WSAS is determined explicitly or implicitly based on a long-term acceptance rate concept that attempts to account for the loss in infiltration rate capacity that occurs in soils as a result of wastewater effluent infiltration (more discussion is given in Section 4). For most situations with individual onsite systems, the effective IS area (i.e., bottom area vs. sidewall vs. both) and the LTAR are incorporated but hidden within a code-prescribed system. For example, a prescribed sizing for a 4-bedroom home on sandy soil might be to provide 60-m of lineal 90-cm wide by 30-cm deep trench. As discussed in Section 4, several attempts have been made to estimate system infiltrative area requirements by selecting an LTAR based on correlation's between a LTAR and soil physical properties (e.g., Ryon, 1928; USPHS, 1967; Jones and Taylor, 1964; Bouma, 1975). Kiker (1948) proposed a fixed reduction factor based on the clean water infiltration rate. Ryon (1928) and later the U.S. Public Health Service (USPHS) (1967) based the assessment on a crude percolation test and a simple empirical relationship. Both of these methods are based on a strong soil dependence of the hydraulic design rate. Based on the imprecision and error of the test and a lack of any correlation between the test results and an LTAR (Bouma, 1971; Healy and Laak, 1974b; Jenssen, 1986; 1988), soil morphology evaluation was promoted as a better method to estimate infiltrative capacity as well as identify depths to limiting conditions in the soil profile (e.g., seasonal perched ground water, low permeability restrictive layers) (e.g., Tyler and Converse, 1994). However, the morphologic description may be best suited to eliminating applications to problem sites and thereby preventing failures as opposed to discriminating a LTAR based on subtleties in soil morphology. Research does suggest lesser dependence of a LTAR on soil properties such as soil texture and greater dependence on wastewater application rate and composition (Jenssen, 1986).

Common practice continues to be that the design application rates for soil absorption systems (trenches or beds) are typically in the range of 1 to 5 cm/d (0.24 to 1.23 gpd/ft^2) (either explicitly or implicitly set) with the site-specific rate based on soil textural properties (e.g., 5 cm/d for a sand and 1 cm/d for a clay loam) and in some areas, percolation testing (e.g., 5 cm/d (1.23 gpd/ft^2) for a 10 minutes per inch (MPI) percolation rate and 1 cm/d (0.24 gpd/ft^2) for a 60 MPI rate). While these relatively low design rates, which are only minute fractions of the respective soil saturated hydraulic conductivities (Ksat), are speculated to represent an LTAR, there are continuing debates regarding the nature and magnitude of LTAR's. Some investigators have reported that an equilibrium or steady-state LTAR actually evolves (Healy and Laak, 1974a; Kropf et al., 1977; Anderson et al., 1982) while others have reported that a continuous, albeit slow, decrease in infiltration rate capacity occurs (Thomas et al., 1966; Okubu and Matsumoto, 1979; Jenssen, 1986). It is likely that an LTAR does not represent a steady-state infiltration rate capacity at which a wastewater absorption system will operate indefinitely when continuously used and in the absence of permeability restoring processes (e.g., soil biota penetration, freeze-thaw effects). Rather, most systems that are operated under continuous use with STE applied at a design rate of 1 to 5 cm/d (0.24 to 1.23 gpd/ft^2) will eventually clog to a degree where hydraulic failure can occur (i.e., the daily application rate exceeds the infiltration rate at time, t (IR_t). The wastewater-induced soil clogging development and hence IR_t is dependent on several factors such as soil morphology (Jones and Taylor, 1964; Healy and Laak, 1974a; Bouma, 1975; Jenssen, 1986), wastewater composition and loading rate (Laak, 1970; Siegrist, 1987a; Duncan et al., 1994; Loudon et al., 1998; Amoozegar and Niewoehmner, 1998; Loudon and Mokma, 1999) and application mode and continuity of use (McGauhey and Krone, 1967; Siegrist, 1987a; Hargett et al., 1982; Tyler et al., 1985). Hence, the clogging process is complex and difficult to model precisely. Most criteria for sizing of soil infiltration systems are therefore still based on empirical data regarding LTAR's (Ryon, 1928; USPHS, 1967; Anderson et al., 1982) with increases in area provided based on implicit or explicit factors of safety added (e.g., conservatively estimated design flows or increased areas for beds over trenches, respectively).

It is emphasized that practices as described above are applicable to domestic wastewater, often from single-family homes. During the 1970's and 1980's, applications began to occur that included different wastewater types and scales of development, such as multiple family dwelling units, restaurants and commercial facilities, and small communities. The WSAS designs for these facilities was initially based on a simple scale-up from that used for single-family homes with little or no adjustment for the performance effects of system size and/or wastewater composition. As a result, hydraulic and purification dysfunctions were reported (e.g., Siegrist et al., 1985a,b; Siegrist et al., 1986; Plews and DeWalle, 1985) which led to modifications in design practice to account for the performance effects of wastewater source type and landscape loading. On the contrary, more dilute wastewaters such as graywater STE, may permit different treatment approaches and equivalent or better public health protection (Siegrist and Boyle, 1982).

3.2. Modifications to Classic System Designs

There are a number of modifications to the classic WSAS as described above that have evolved to improve its performance capabilities and/or reliability (see Tables 1 and 2). Modifications of the wastewater source can be made to reduce the volume of wastewater to be treated and/or its pollutant load through (1) flow reduction (e.g., water conserving fixtures) (Siegrist et al., 1978), (2) waste segregation (e.g., no garbage disposal, urine separation, or graywater vs. black water separation) (Siegrist, 1978; Siegrist and Boyle, 1982: Jenssen and Skjelhaugen, 1994; Rasmussen et al., 1996), (3) in-house recycle (e.g., graywater for toilet flushing) (Anderson et al., 1981; Siegrist et al., 1981), and/or (4) point of use treatment (e.g., bag filter on laundry discharges) (Fig. 6). Modifications to septic tank designs have been targeted at STE quality, particularly with respect to reducing the STE suspended solids concentration and to a lesser extent the BOD_5, and thereby prevent accelerated clogging of soil absorption systems. Examples of these include the use of septic tank effluent biofilters units (see Fig. 7a).

Fig. 6. Examples of wastewater source modifications: (a) 3-L volume flush toilet, (b) compost toilet, (c) graywater recycle unit, and (d) point-of-use bag filter for laundry discharge.

Modifications or variants to the soil infiltrative surface have been directed at improving infiltration capacity through changes to the interface character and its geometry and placement in the soil profile. Research related to the rate and extent of soil clogging in WSAS with gravel aggregate on the infiltrative surface (aggregate-laden) led to the development and use of infiltration systems which have an open surface without a layer of aggregate on it (aggregate-free), the most common of which is a chamber system (see Fig. 4) (Tyler et al., 1991; Keys, 1996; May, 1996; Loudon et al., 1998; Van Cuyk et al., 2000). Based on the potential adverse effects of gravel on short- and long-term infiltration capacity (e.g., compaction, fines, embedment, and focused pollutant loading), these aggregate-free systems are designed with infiltration areas on the order of 40% to 50% less than required with gravel systems (see Fig. 4). Geometry and placement in the soil profile can be selected to maximize infiltrative surface area and enable delivery of effluent into the soil where the treatment potential is highest. Increasingly, the use of narrow trenches (e.g., 15- to 30-cm wide) that are placed shallow in the soil profile (e.g., 30- to 60-cm depth) is being promoted (see Fig. 5). Soil permeability is usually higher shallow in the profile and more importantly, narrow and shallow placement improves aeration potential. The use of at-grade and low pressure pipe (LPP) systems were designed to place the infiltration surface very near the land surface while mound systems place it in an imported layer of sand fill. These system types are intended to overcome site limitations associated with an inadequate unsaturated zone thickness beneath an IS (Converse et al., 1978; Tyler and Converse, 1985; Stewart and Reneau, 1988; Converse et al., 1991; Hoover and Amoozegar, 1989; Amoozegar et al., 1994). Such limitations are most often due to the presence of a low permeability layer, seasonal or permanent high water table, and/or porous or fractured bedrock.

Modifications to the classic WSAS also encompass the method of delivery and frequency of application of wastewater effluent to the soil (see Fig. 5) (Otis et al., 1978). With the addition of a pump or siphon to the system, intermittent dosing into conventional 10-cm (4-in.) diameter perforated pipe can enhance the delivery of STE to a soil absorption system (see Fig. 5). Compared to the normal, gravity delivery that results in a semicontinuous trickle flow that is randomly and non-uniformly distributed, dosing improves intermittent delivery of STE and improves the distribution somewhat. If small diameter (e.g., 2.5-cm) perforated (e.g., 3.2-mm orifices) pipe is used, a pump or siphon can produce pressurized distribution of the dosed effluent which can lead to more uniform application of the loading to the soil system. Early research led to guidance that dosing frequencies should be 1 to 4 times per day based on waste generation characteristics and pressurized dosing networks should be designed to achieve relatively equal headlosses and flow rates between orifices (Otis et al., 1978). Later, Hargett et al. (1982) showed that pressurized dosing offered little advantage over gravity fed application in a silt loam soil since, with both delivery methods, soil clogging evolved to the extent that the infiltrative surface was continuously ponded and fully utilized in both loading regimes. A recent innovation includes the concept of timed dosing through pressurized distribution networks where the septic tank provides equalization capacity to permit frequent dosing. This is thought to enable more uniform application and enable more unsaturated flow through the unsaturated zone beneath the infiltrative surface, thereby aiding treatment.

An important development which might be viewed as a modification to the classic WSAS, includes the array of devices and equipment that have evolved to enable process control and monitoring of system function and performance. For example, the addition of control panels with hydromechanical sensors and telemetry features have provided a means by which to control effluent application to a soil absorption unit, to record effluent loading rates, and to detect gross system dysfunction and correct it early. Control and monitoring of purification still relies on sampling and analysis, which is easy for end-of-pipe locations but difficult for soil solution and ground water.

3.3. Alternative Unit Operations to Classic System Designs

Alternatives to the classic system design involve major changes in the unit operations and treatment train within the system (Fig. 7) (see Tables 1 and 2). These alternatives can be categorized to include (A) add-on treatment units to a septic tank, (B) anaerobic unit operations as replacements for a septic tank, (C) aerobic package plants, and (D) engineered porous media biofilters (PMB's). The primary purpose of these alternatives has been to (1) provide a measurable improvement in BOD_5 and SS removal (group A); (2) remove nitrogen from STE before discharge to a WSAS thereby reducing nitrate contamination of ground water (group B), (3) markedly reduce the BOD_5 and SS concentrations in STE before discharge to a WSAS thereby retarding soil clogging (group C and D) and/or (4) produce an effluent suitable for disinfection and discharge to the land surface (disposal only or beneficial reuse such as landscape irrigation) or a receiving water (group C and D).

Add-on units (AOU's) are relatively simple in design and operation and include (1) specially designed effluent filters which support biomass growth and SS removal (Fig. 7a) and (2) submerged media filters with aeration and recirculation provided by a simple air-lift pump to provide some BOD_5 removal (Fig. 7b). The treatment efficiency of these AOU's remains somewhat speculative as there have been few if any experimental studies documenting performance.

Anaerobic upflow filters were envisioned as means of equal or better treatment with less susceptibility to upset and high concentrations of SS being released into the STE. These systems were comprised of rock-filled tanks with an upflow flow regime to aid in distribution through the media. Performance observations suggest the filter's performance is comparable to that of a well-designed septic tank, and possibly improved in some cases (Kennedy, 1982).

Aerobic package plants based on fixed film or suspended growth processes were down-scaled from traditional designs in an effort to produce an effluent quality suitable for infiltration in low permeability soils and/or for discharge with disinfection to the ground surface or a receiving water (see Fig. 7c). While these systems were shown to have the inherent ability to produce a higher quality effluent than STE, they were subject to mechanical malfunctions and process upsets (Hutzler et al., 1978; USEPA, 1978; 1980; NSF, 1996). Thus, to reliably achieve their system performance capabilities, operation and maintenance (O&M) must be provided.

Advanced treatment has been demonstrated with PMB's comprised of a bed of sand (Fig. 7d), peat, foam (Fig. 7e), textiles, or other granular media (see Fig. 7) that are intermittently loaded (e.g., 4 to 24 times per day) at hydraulic loading rates that are much higher than those for a soil WSAS (e.g., 5 to 20 gpd/ft^2 vs. $\leq$1 gpd/ft^2) (Anderson et al., 1985; Effort et al., 1985; Jowett and McMaster, 1994; Loomis and Dow, 1998; Crites and Tchobanoglous, 1998; Driscoll et al., 1998; Roy et al., 1998; Van Cuyk et al., 2000). The higher loading rates are enabled by coarse particle diameters and design, which allows easy access to the medium to clean and/or replace it if, needed. These PMB's are being advocated and used to provide higher quality effluents thereby reducing the purification that the soil absorption system must achieve as well as reducing soil clogging and enabling higher application rates. Most PMB systems can yield substantial reductions in BOD_5 and SS as well as complete nitrification and even some N-removal (Lamb et al., 1990; Loomis and Dow, 1998). Microbes can be reduced by a factor of 10 to more than 1000, but there still can be pathogenic bacteria, viruses and protozoa in the effluent (Emerick et al, 1997; Higgins et al., 1999; Loomis and Dow, 1998; Van Cuyk et al., 2000). While small-scale onsite disinfection units (e.g., chlorination, ultraviolet light irradiation) are available, they are rarely used prior to subsurface soil absorption.

PMB's have also been applied to achieve nitrogen removal in an otherwise classic WSAS. The nitrified effluent from a PMB (e.g., trickling filter, textile filter, or sand filter) is directed back to the influent end of the septic tank (Whitmayer et al., 1991). The anaerobic conditions in the tank combined with adequate carbon and nitrate as an electron acceptor have been shown to enable nitrogen removal, on the order of 50 to 80% or higher in some cases, thereby yielding STE concentrations of 20 mg-N/L or less (Shafer, 2000).

Beneficial reuse of wastewater effluent has been accomplished through graywater treatment systems producing effluent for flushing water carriage toilets and/or landscape irrigation (Anderson et al., 1981). A recent innovation involves the application of drip irrigation tubing and emitters to deliver STE to the shallow subsurface into the root zone (see Fig. 7f) (Sinclair, et al., 1999). To prevent emitter plugging, a spin-disk filter apparatus is used to remove suspended solids normally found in STE.

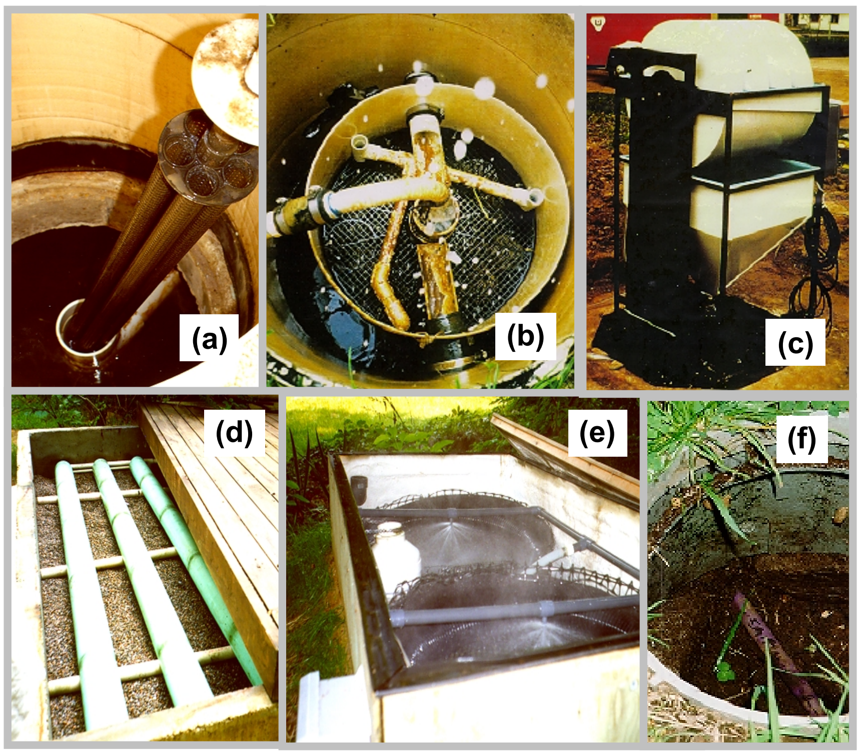

Fig. 7. Examples of alternative unit operations including: (a) effluent biofilter unit, (b) in-tank aeration unit, (c) rotating biological contactor, (d) sand filter, (e) foam filter, and (f) drip irrigation line.

4. Performance Capabilities, Predictability, and Reliability

4.1. General Performance Capabilities of WSAS

The performance achieved by a modern WSAS depends on a number of inter-related factors. Engineering design is completed for a given application based on a site evaluation. This leads to construction and startup, followed by system usage, and any requisite O&M. If all of these factors are properly addressed, and the actual conditions and usage are consistent with any assumptions made, then system performance should be as described below. However, if any of these factors are overlooked or inadequately addressed, or if actual conditions depart from assumptions made in design and implementation, then performance deficiencies can occur either early or late in the system's life. These deficiencies can manifest themselves as mechanical, hydraulic, and/or purification dysfunctions and all three can increase the risks of adverse public health and environmental effects (see Fig. 3). Purification dysfunctions that lead to ground water and surface water contamination and are of particular concern since they can be difficult to monitor for, detect, and mitigate.

The design of any WSAS inherently includes subsurface infiltration and percolation for advanced treatment and disposal of a partially treated effluent, most often STE. As noted earlier, these systems typically employ delivery of primary treated wastewater into a soil absorption trench or bed from which wastewater infiltrates and percolates through a depth of soil into underlying ground water (see Figs. 1 and 2) (Anderson et al., 1985; Brown et al., 1979; USEPA, 1978, 1980, 1981, 1992, 1997; Kristiansen, 1982, 1991; Jenssen and Siegrist, 1990; Crites and Tchobanoglous, 1998). Effective purification requires adequate hydraulic retention time (HRT) and suitable conditions for treatment processes to function (e.g., adequate biomass and bioactivity, aerobic conditions, favorable pH and temperature) such that processes occur at a rate and extent to achieve removal (e.g., sorption/precipitation), transformation (e.g., biodegradation) and die-off/inactivation before ground water recharge occurs (see Fig. 2). The percolate moving downward from the WSAS may be mixed with ambient ground water, which migrates under, natural gradients toward points of exposure to receptors of concern (see Fig. 3). Depending on local and regional conditions, transport/fate processes along the pathways to receptors may or may not reduce residual concentrations of COC's in the percolate from a WSAS that are above threshold concentrations to lower levels that are no longer of concern.

For effective purification of primary treated wastewater in natural soils, unsaturated flow in the porous medium can be critical since this controls contact between wastewater constituents and soil particles and associated biofilms, over an adequate period for treatment processes to occur (Bouma, 1975; USEPA 1978; Jenssen and Siegrist, 1990; Emerick et al., 1997; Schwager and Boller, 1997; Stevik et al., 1999; Van Cuyk et al., 2000; McCray et al., 2000). Unsaturated flow conditions can be achieved by application of limited daily loadings (e.g., 1 to 5 cm/d) which are usually a minute fraction of the medium's K_{sat} (e.g., 100 to 1000 cm/d). Intermittent dosing (e.g., 4 to 24 times per day) and pressurized uniform application can also be employed to help create an unsaturated flow regime. Also, in time, wastewater-induced soil clogging evolves due to an accumulation of inert particles and amorphous organic matter (like humic-substances) in a few cm-thick zone at the IS (see Fig. 2) (Otis, 1985; Jenssen and Krogstad, 1988; Siegrist, 1987a; Siegrist et al., 1991). This clogging leads to a reduced permeability and more uniform temporal and spatial infiltration with a concomitant unsaturated flow almost independent of wastewater loading. When soil-clogging is extensive, STE may continually pond on the horizontal infiltrative surface thereby causing vertical sidewalls to become available for infiltration. Soil clogging is an important, if not critical, process, which contributes to the advanced treatment potential of WSAS. Not only does it enhance infiltration surface utilization and yield an unsaturated flow regime in the vadose zone, it provides powerful treatment in the clogging zone. However, if soil clogging yields too great a reduction in permeability at the IS, it can be detrimental by causing hydraulic dysfunction (e.g. backup into a dwelling or seepage to the ground surface) or adversely affecting purification (e.g., anaerobic conditions and reduced biotransformation rates).

For the common wastewater chemical COC's such as BOD_5, COD, and SS, purification efficiencies of >90% can be sustainably achieved by filtration, sorption, and biodegradation processes in most WSAS and settings (see Fig. 2; Table 2) (USEPA, 1978; 1980; Jenssen and Siegrist, 1990; Van Cuyk et al., 2000). With dilution and dispersion in the ground water and any additional removal therein, these COC's seldom present any concern for adverse impacts to the receiving environment. However, nutrient removal (nitrogen and phosphorus) and any adverse impact on a receiving environment are much more sensitive to process design and site conditions (Gold and Sims, 2000). Microbial COC's commonly found in STE include pathogenic bacteria at sustained, high concentrations and virus and protozoa at highly variable and episodically released levels (see Table 2) (Bicki et al., 1984; Anderson et al., 1985; USEPA, 1978; Van Cuyk et al., 2000; Cliver, 2000). While WSAS performance has been documented for bacteria such as fecal coliforms, there is less information on purification with respect to pathogenic bacteria, viruses, and protozoa. Purification efficiencies in WSAS can be very high, yielding near complete removal of fecal coliform bacteria and 99.99% or higher reductions in virus (Emerick et al., 1997; Stevik et al., 1999; Van Cuyk et al., 2000). Despite excellent purification performance observed in controlled experiments (e.g., Van Cuyk et al., 2000) and field studies with properly implemented modern systems (e.g., Anderson et al., 1991, Higgins et al., 1999, Oakley et al., 1999), the transport of pathogens from WSAS to ground water, and in some cases, drinking water has been alleged (e.g., Rose et al., 1999). However, the factors causing the transport were often not documented, or the WSAS studied were of older disposal-based designs.

Apart from purification efficiency, the hydraulic function of a WSAS is often gauged by its service life. Service life is closely related to soil clogging and the daily loading rate vs. the long-term acceptance rate, which in turn are influenced by an operational loading factor (LF = ratio of actual loading to design loading) and continuity factor (CF = days of use divided by 365). At low LF's or for low CF's, service lives may be practically indefinite. Several studies of system service life have been completed during the past 25 yr. suggesting hydraulic service lives varying from 11 to >30 yr. (see Fig. 8) (Hill and Frink, 1980; Hoxie and Frick, 1984; Plews and de Walle, 1985; Gårderlokken, 1997; Sherman et al., 1998; Keys et al., 1998). Hill and Frink (1980) studied more than 3000 small systems and concluded that a service life of more than 30 years could be expected. Plews and de Walle (1985) studied 369 large, buried systems and found that more than 60% had a hydraulic service life of more than 20 years. For systems with an actual loading rate of < 4 cm/d only 3.8% had poor hydraulic performance. For Norwegian systems built after 1985 when new regulations and loading rates of 2.5 cm/d or less where applied to most systems, no reports of hydraulic failure of properly installed systems have been reported (Gårderløkken, 1997). This suggests that for standard domestic STE applied to gravel-filled infiltration trenches and loading rates <2.5 cm/d, a hydraulic service life of several decades can be expected for WSAS that are designed and constructed today and operated and maintained as needed based on the design specifications. On the contrary, Sherman et al. (1998) showed 18 years as the mean age of failure in three counties investigated in Florida while Keys et al. (1998) predicted that gravel-filled systems in sand soils have a predicted life of 11 years, even when loaded as low as 1.6 cm/d. For other wastewater effluent types and sorted soils, coarse sands and gravels, Jenssen and Siegrist (1991) suggested a conceptual framework for hydraulic loading rates for subsurface treatment systems. However, no data are available on service life for alternative system designs.

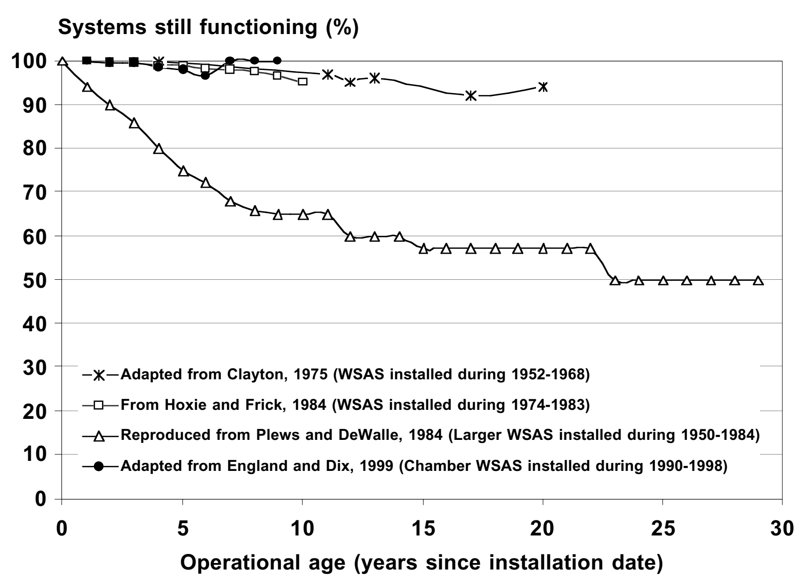

Fig. 8. System hydraulic function versus operational age and installation period.

4.2. WSAS Treatment Potential for Key Pollutant Groups

The common COC's in domestic wastewater and reasonable performance expectations for modern system designs that are properly implemented (i.e., proper siting, design, installation and operation/maintenance) are summarized in Table 2. Additional details regarding three key pollutant groups, (1) organics and suspended solids, (2) nutrients, and (3) pathogens, are given in this section.

4.2.1. Organics and Suspended Solids. Biodegradable organics in either dissolved or suspended form can be characterized by the BOD_5. Volatilization and adsorption, followed by microbial degradation are the main processes for removal of soluble biodegradable organics. Suspended solids, including organic and mineral matter, can be removed through a combination of physical straining and biological degradation processes (Reed et al., 1994). Most soils are effective porous media biofilters due to narrow pores and effective straining of wastewater particles. The large surface area of the soil particles also provides a great potential for biofilm development and infiltration systems are reported to attain maximum efficiency with respect to removal of organic matter as early as of 2 to 3 weeks from the onset of operation (Pell and Nyberg, 1989a,b). Others report a period of 2 to 3 months before the biological degradation potential is fully developed (Van Cuyk et al., 2000). In either case, the start-up phase may be of little consequence to overall public health and environmental protection given the service life of most WSAS is years in length. When viewed over their long service lives, most WSAS can be expected to reliably achieve very high removal of BOD_5 and SS (Hines and Favreau, 1975; Anderson et al., 1985; Effert et al., 1985; Soltman, 1990). Organic chemicals such as volatile organic compounds (e.g., benzene, trichloroethylene) and pesticides can be present in domestic wastewater (Greer, 1987; Kolega et al., 1987; Bicki and Lang, 1991; Sauer and Tyler, 1991; Sherman and Anderson, 1991). However, the concentrations appear to be at trace levels, which do not migrate and pose problems in most WSAS treating domestic wastewater.

4.2.2. Nutrients. In domestic wastewater, typically 70-90 % of the nitrogen is in the form of ammonium ion (NH_4^+) and 10 to 30 % is in organic form (Lance, 1972; Nilsson, 1990; Gold and Sims, 2000). The removal mechanisms for nitrogen in a WSAS include volatilization, ammonification, nitrification/denitrification and matrix adsorption. For a properly installed system, the predominant N-retention reaction would be ammonium adsorption while the predominant transformation reaction would be biological nitrification. The principal removal reactions include biological denitrification and leaching and under certain conditions also chemical denitrification in the ground water zone (Siegrist and Jenssen, 1989). Nitrogen removal in wastewater infiltration systems vary greatly. In general near complete nitrification is achieved in properly installed systems, and nitrification is normally very rapid occurring in the first 30 cm of soil below the infiltrative surface. However, 1-2 months are required from the onset of infiltration to generate a full population of nitrifiers (Pell and Nyberg 1989a,b; Zhu 1998; Van Cuyk et al., 2000). A removal of 10 - 20% of the total nitrogen applied can normally be achieved in conventional WSAS (Siegrist and Jenssen, 1989; Westby et al., 1997; Converse, 1999). Higher removal is possible in mound systems and those with cyclic loading/resting. Westby et al. (1998) found an average of >85% N-removal in dosed mound systems. In systems optimized for nitrogen removal, more than 50% removal can normally be achieved (Lance et al., 1976; Laak, 1982; Siegrist and Jenssen, 1989; Converse, 1999). Phosphorus is typically present in wastewater as orthophosphate, dehydrated orthophosphate and organic phosphorus. Biological oxidation results in conversion of most phosphorus to the orthophosphate forms (Cooper et al., 1996). The main processes for phosphorus removal from wastewater in porous media are adsorption, complexation and precipitation. Most models assume that phosphorus fixation in a PMB occurs in two consecutive kinetic reactions: rapid physical adsorption followed by a slower chemisorption (Tofflemire et al., 1973; Sikora and Corey, 1976; Gold and Sims, 2000). Calcium and oxidized compounds of Fe and Al are known to be important agents for P-sorption in soils. Stuanes and Nilsson (1987) documented that the Fe and Al pools were the most important P-sinks in soils receiving STE. The potential for P-sorption of a porous medium is dependent on the mineral composition and the degree of weathering of the particle surfaces which renders the metals in an oxide or hydrous oxide state where they are able to react with P compounds. In general, soils have variable P-sorption ability (e.g., 0.2 to 1.2 g-P/kg). In a quartz sand the P-sorption capacity of a wastewater infiltration system may become saturated after a few months whereas in weathered sand or fine grained soils (e.g., clays, silt, loam) the sorption capacity may hold for a period of ten years or more. Most studies of P removal have evaluated the sorption potential using equilibrium isotherms, often described by the Langmuir equation (Ellis and Ericson, 1969; Tofflemire et al., 1973; Johnson et al., 1979; Sommers et al., 1979). Experimental results often show that the P-sorption capacity of the PMB is actually much higher than estimated by an equilibrium isotherm (Stuanes and Nilsson, 1987). However, even though many studies assume sorption to be instantaneous, it has been shown by several researchers that this is not always the case (Haseman et al., 1950; Coleman et al., 1960; Davidson and Chang, 1972; Enfield, 1974; Kuo and Lotse, 1974). Overman et al. (1978) reported that the assumption of equilibrium between solution and adsorbed phases in wastewater PMB's was reasonable for lower wastewater flow velocities but less suitable for higher velocities, the latter of which might occur for shallow depths in coarse PMB's or at high loading rates.

4.2.3. Pathogens. Microbiologic COC's commonly found in STE include pathogenic bacteria at sustained high concentrations and virus and protozoa at highly variable and episodically released levels (Cliver, 2000). From a single family home, wastewater bacterial densities are typically quite high with values of 10^8 to 10^{12} organisms per L being commonly encountered (Bicki et al., 1984; Anderson et al., 1985; USEPA, 1978; Haas et al., 1999; Van Cuyk et al., 2000). Of the total bacterial density there can be prevalent, but highly variable, concentrations of pathogenic bacteria like *E. coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Salmonella*. Other pathogens, such as virus and protozoa, are not continuously present at high densities, but rather are shed during disease events and thus the concentration in the wastewater stream at a given home can vary from non-existent levels to values on the order of 10^6 organisms per L or more. Even domestic graywater can contain appreciable levels of pathogens (Siegrist and Boyle, 1982; Rose et al., 1991). Multiple family homes or clusters of individual homes tend to attenuate the episodic nature of pathogen release, but increase the likelihood that the wastewater will contain pathogens at any given time. Pathogens may also be more prevalent in commercial and institutional sources and in some cases, at very high levels (e.g., highway rest areas).

Numerous investigations have studied the transport and fate of bacteria and viruses in soil and ground water under laboratory and field conditions (Romero, 1970; McCoy and Ziebell 1975, USEPA, 1978; Lewis et al., 1982; Harvey and Garabedian, 1991; Tuetsch et al., 1991; Yates and Ouyang, 1992; Harvey, 1997; Higgins, 1999; Oakley et al., 1999; Stevik et al., 1999; Van Cuyk et al., 2000). Studies of bacterial transport/fate have most often employed fecal indicator bacteria such as fecal coliforms or enteric bacteria such as *E. coli*. Studies of virus transport/fate have often been accomplished using bacteriophages such as MS-2 or PRD-1. In general it can be concluded that bacteria and viruses are transported only a few decimeters to meters in the unsaturated zone whereas in the ground water (saturated) zone, they can travel ten to hundreds of meters (Keswick and Gerba, 1980; Keswick et al., 1982; Lewis et al., 1982; Rose et al., 1999). In WSAS removal and inactivation/die-off of pathogens can be extremely effective during STE infiltration through the clogging zone and percolation through the unsaturated flow regime beneath it. The mechanisms for immobilization of bacteria and viruses in WSAS are a combination of straining and adsorption (Peckdeger and Matthess, 1983; Sharma et al., 1985). Straining of bacteria can occur if the pores of the filter are smaller than the bacteria. According to Updegraff (1983) straining becomes an effective mechanism when the average cell size is greater than the grain size d_5 of the soil (d_5 is the diameter where 5% of the particles in mass are smaller and 95% of them are larger). Bouwer (1984) reported that straining occurred when the diameter of the suspended particle was larger than 0.2 times the diameter of the particles constituting the porous medium. A more sophisticated criterion for filtration of bacteria under saturated conditions than the two mentioned above was suggested by Matthess and Peckdeger (1985). Results form straining experiments have shown that in addition to media grain size, straining is controlled by the amount of mechanical and biological clogging of the media, the degree of water saturation, and the hydraulic loading rate (Peckdeger and Matthess, 1983; Corapcioglu and Haridas, 1984). The work of several investigators (e.g., McCoy and Ziebell, 1975; Van Cuyk et al., 2000) has shown that clogging can be of essential importance in pathogen cell removal. This is partly due to reduction of pore size, which induces straining, but also to biotic factors and adsorption, which may increase in importance when clogging, is present.

When the pores are larger than the microorganism, adsorption becomes the dominant retention mechanism; adsorption is therefore of great importance to virus removal. Adsorption of cells to a porous media is dependent on several factors as the content of organic matter, degree of biofilm development, and electrostatic attraction due to ion strength of the solution or electrostatic charges of cell- and particle surfaces (Stevik et al., 1998). Coating of Fe-oxides on media surfaces is shown to enhance adsorption of bacteria and viruses (Keswick and Gerba, 1980). This is due to the Fe-oxides turning the surface charge more positive and thereby increasing the adsorption of bacteria that normally have a negative surface charge at neutral pH. Iron oxides also enhance phosphorus removal (Stuanes and Nilsson, 1987) and hence a positive correlation between phosphorus and bacteria/virus sorption can be expected. Adsorption of microbial cells is a two-step process that can be reversible or irreversible. Reversible adsorption is a weak interaction between the bacteria and the porous media, and the primary forces are electrostatic forces and van der Waals' forces (Mozes et al., 1986). Irreversible adsorption, or adhesion, is a permanent interaction that occurs when bacterial polymers connect the bacteria and the adsorbent (Griffin and Quail 1968; Marshall 1971; Elwood et al., 1982). Die-off of bacteria and inactivation of virus can occur in the adsorbed or in the liquid phases. These processes are affected by biotic and abiotic factors such as soil water content, pH, temperature, organic matter, bacterial species, predation, and antagonistic symbiosis between microorganisms in the system (Yates and Ouyang, 1992; Stevik et al., 1999).

4.3. Factors and Processes affecting Performance

The performance capabilities as noted above are influenced by various factors and their interactions. While it is impossible to isolate a single factor and describe its effect on WSAS performance, Table 3 lists some key factors and the following discussion is given to illustrate the nature and types of effects that can occur. Soil and site conditions are described first followed by system design, installation, and operation/maintenance. For the purposes of this discussion, the WSAS treatment system encompasses the inlet to the soil absorption unit through the lower limit of the underlying vadose zone (see Fig. 3).

4.3.1. Soil and Site Conditions. *Soil properties* such as grain size and pore size distribution, bulk density, porosity, water content, surface area, mineralogy, organic matter content, pH, and microbial biomass and diversity are very important to flow and transport processes in WSAS. Also important are any heterogeneities in these properties with horizontal and depth dimensions. The infiltration zone, unsaturated zone, and ground water zone are all important regions of interest. As noted earlier, long-term acceptance rates have historically been linked with soil texture (e.g., sand, silt loam) and a crude measure of hydraulic capacity (i.e., percolation rate). However, there is little research evidence that has established the relationship between LTAR's and soil properties and some evidence to the contrary. Jenssen (1986) conducted column experiments that revealed that for time periods less than 2 yr., the infiltration rate is dependent on the K_{sat} of the soil. However, for longer times and for soils with an initial saturated hydraulic conductivity below 2500 cm/d (sands range from 50 – 10000 cm/d) the clogging development seems to control the infiltration rate (Fig. 9). Jenssen concluded that there should be little need for differentiation of the loading rate based on soil type for standard gravel-filled soil absorption units receiving domestic STE in fine sands and soils of lower hydraulic conductivity (clayey, loamy and fine sandy soils). However, the actual flux rate through a soil clogging zone can be impacted by the moisture potential underneath it which is controlled by soil texture and unsaturated zone depth, as well as the head of ponded effluent above it (Bouma, 1975).

Table 3. Design and environmental conditions affecting WSAS performance.

Category	Factor/condition	Example performance effects
Soil and site conditions	Soil system properties and heterogeneity within the WSAS	Grain size and pore size distribution, bulk density, porosity, water content, surface area, mineralogy, organic matter content, pH, and microbial biomass can affect flow and transport processes.
	Unsaturated zone depth between the infiltrative surface and ground water	Distance can affect hydraulic function and in turn purification by influencing the soil water content, aeration status, media surface area, and hydraulic retention time.
	Soil temperatures	Can influence soil hydraulic conductivity properties based on viscosity effects; can affect the solubility of dissolved gases such as O_2 and the rate and extent of biological reactions; virus inactivation is highly temperature dependent with higher rates at higher temperatures.
Design features	Effluent application rate and composition	Can affect the rate and extent of clogging at the infiltrative surface, which in turn can affect the hydraulic flow regime and treatment within the WSAS.
	Method of effluent application	Can influence performance depending on the COC and the type and rate of reactions effecting its treatment.
	Depth and geometry of the infiltrative surface	Can affect moisture, temperature, and aeration regimes, and the degree to which diurnal and seasonal variations occur. Can affect degree of biogeochemical reactivity within the infiltration and vadose zones (shallower depth is typically more reactive).
	Infiltrative surface interface characteristics	Presence of an aggregate such as gravel on an infiltrative surface can reduce ISZ permeability by blocking pore entries, becoming embedded in the soil matrix, yielding fines that are deposited in pore entries, or by focusing BOD and TSS as a result of the reduced permeability.
	System size and density of application	As systems become larger and/or the density of application of small systems increases, there is increased potential for adverse hydrologic effects (e.g., ground water mounding) and cumulative pollutant effects.
Construction and operation	Construction practices	Can affect the hydraulic properties of the natural, undisturbed subsurface through compaction, smearing or puddling of the surface due to shear from a vehicular tire or track at the ISZ interface, or deposition of wind-blown materials.
	Age of installation and operational service life	The age of installation is important as the state-of-knowledge and standard of practice have evolved over the past 50 years and systems installed in 1950 are not the same as those installed in 1990. Operational service life combined with age of installation can affect system performance, primarily due to the rate and extent of clogging.
	Operation/maintenance	Changes in wastewater flow/composition from design assumptions can impact overall performance; maintenance through pumping and hydromechanical repair as needed is important to long-term function.

Unsaturated zone thickness beneath a soil absorption unit and the depth to ground water can affect hydraulic function and in turn purification by influencing the soil water content, aeration status, media surface area, and hydraulic retention time. In the U.S., the thickness of the unsaturated zone for WSAS range from 0.6 to 1.2 m and for intermittent sand filters, from 0.6 and 0.9 m (USEPA, 1980a; Anderson et al., 1985; Crites and Tchobanoglous, 1998). A high degree of treatment normally occurs in the infiltration zone as soil clogging develops. However, at higher hydraulic loading rates and with nonuniform distribution methods, constituents of concern that would normally be treated can be transported through the vadose zone to ground water.

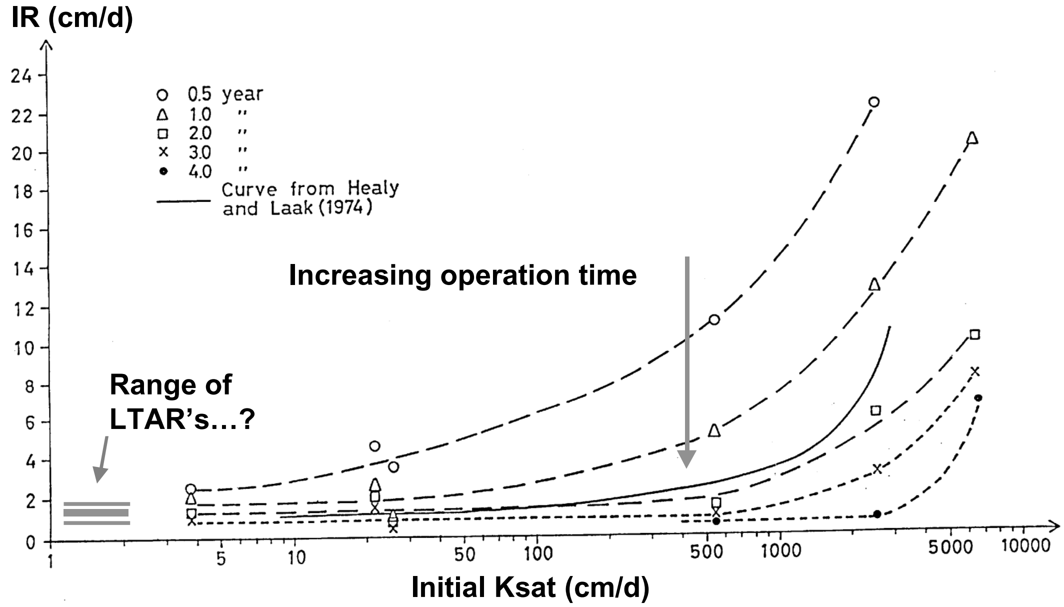

Fig. 9. Time-dependent infiltration rate changes during wastewater application related to the initial saturated hydraulic conductivity of the media for clean water (from Jenssen, 1986).

For example, many studies have shown that a large percentage of bacteria remain near the IS when effluents are applied to porous media (Brown et al., 1979; Kristiansen, 1981; Duncan et al., 1994; Smith et al., 1985; Huysman and Verstraete, 1993; Emerick et al., 1997; Stevik et al., 1999; Van Cuyk et al., 2000). Kristiansen (1981) found no fecal coliform bacteria at more than 30-cm depth below the infiltrative surface of an onsite soil absorption system with a mature clogging zone. Duncan et al. (1994) evaluated the relationship of pretreatment and soil depth on percolate composition and found high removals of fecal coliforms within the first 30 cm for all pretreatment methods. The authors concluded that higher levels of pretreatment could be substituted for increased soil depth. Stevik et al. (1999) found a significant reduction of *E.coli* with soil depth and observed that 99% of *E. coli* was removed in the top 12 cm of 80-cm long columns packed with sand media. Emerick et al. (1997) observed that intermittent sand filters as shallow as 38 cm were capable of removing 90 percent of coliform bacteria from wastewater with a high dosing frequency and a hydraulic loading rate of 4.0 cm/day. Van Cuyk et al. (2000) completed 3-D lysimeter studies and field monitoring of mature systems to quantify the fate of indigenous fecal bacteria as well as viral surrogates (MS-2 and PRD-1 bacteriophages). Lysimeter results revealed breakthrough of fecal coliforms and virus in sand regardless of depth to ground water (60 vs. 90 cm) or infiltrative surface/loading rate scenario (gravel-laden at 5.0 cm/d vs. gravel-free at 8.4 cm/d) (Masson, 1999; Van Cuyk et al., 2000). However, if hydraulic loading rates are too high or the dosing frequency is too low, some microbes can be transported to lower regions in a soil matrix, posing a purification concern in systems that are too shallow to ground water. Alternatively, at some point there is limited additional improvement in purification by increasing unsaturated zone thickness (Peeples et al., 1991).

The thickness of unsaturated soil beneath an IS is not fixed. Rather, it can be quite variable due to changing ground water table elevations associated with seasonal precipitation, or to excess infiltration due to wastewater application. When wastewater is applied to soil, the ground water recharge in the area of infiltration increases. This can result in a local increase in ground water level termed ground water mounding (Hantush, 1967; Fielding, 1982). The ground water mounding is dependent on several factors, such as the saturated hydraulic conductivity of the soil, distance to hydraulic barriers, and depth of the saturated layer (see Fig. 10). The loading rate and design of the system also will influence the height of the ground water mound. In some tills and fine grained soils, the ground water can rise several meters due to wastewater application to a WSAS. Jenssen (1988) therefore defined the hydraulic capacity of a site as "...the amount of liquid per unit time that can be continuously infiltrated without raising the ground water table above an acceptable level". The hydraulic capacity is most likely to be limited in soils of low hydraulic conductivity or shallow depth. In such soils the hydraulic capacity should not be overlooked even when designing small systems. Mound systems are built in shallow soils of low hydraulic conductivity and failure of mound systems (at least in Norway) is due to insufficient considerations of the hydraulic constraints at the site. Ground water mounding must be considered on sites with hydraulic limitations and/or where the wastewater application rate per unit area increases due to clusters of small WSAS or with larger commercial or smaller community systems. Modeling tools are available to aid in the analysis of mounding under WSAS (see Table 4).

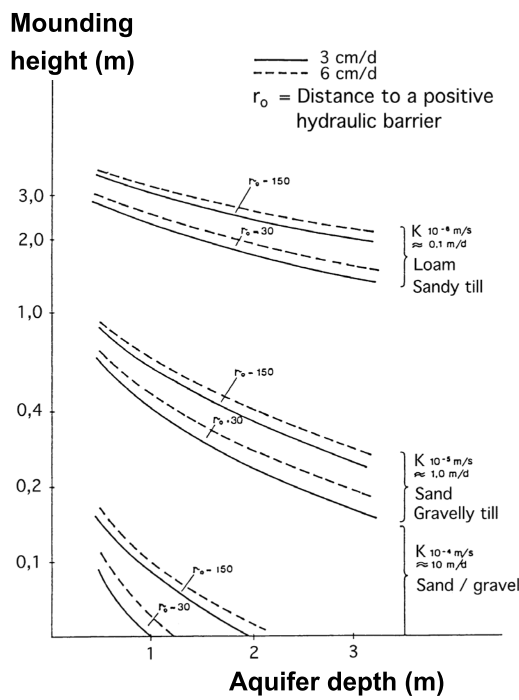

Fig. 10. Ground water mounding under WSAS as a function of infiltration rate, aquifer depth and hydraulic conductivity, and distance to a hydraulic barrier (after Jenssen and Bromssen, 1985).

Soil temperatures can influence the hydraulic conductivity properties of a porous medium like soil, due to the effects of temperature on water viscosity. Comparing a temperature of 10C to that of 30C, the hydraulic conductivity is lower and the moisture retention is higher under otherwise comparable conditions. Soil temperature can also affect the solubility of dissolved gases such as O_2. The rate and extent of biological reactions can be described by an adaptation of the Arhennius relationship for chemical reactions which indicates that for a 10C decrease in temperature, the rate of reaction is 50% as fast. Some biological processes (e.g., nitrification) can effectively cease at very low (<10C) or high temperatures (>40C). Virus inactivation is highly temperature dependent with higher rates at higher temperatures (Yates and Ouyang, 1992).

Climate considerations are diverse and include air temperatures, relative humidity, wind speed, precipitation, and so forth. These characteristics can influence the unsaturated zone properties with respect to temperature and water content. Air temperature and relative humidity characteristics can influence the rate of evapotranspiration. This can be an important route for water movement in warm, dry climates. Precipitation in the form of snow can provide an insulating layer on the land surface that can help maintain subsurface temperatures above freezing and enable shallow effluent infiltration all year round. The precipitation characteristics of a region are important as they affect the moisture regime of the subsurface at a site. It not likely that precipitation will dramatically effect system function on sloping sites due to runoff as opposed to infiltration. However, on some sites, precipitation events have been linked to release of COC's such as virus, from a subsurface soil zone.

4.3.2. WSAS Design Features. *Effluent application rate and composition* can affect the rate and extent of clogging which in turn affect the long-term acceptance rate of the soil absorption unit (Siegrist et al., 1987b; Jenssen and Siegrist, 1990; Duncan et al., 1994; Tyler and Converse, 1994). Clogging zone genesis has been shown to be a function of the mass loading rate of wastewater constituents including biochemically oxidizable substances and suspended solids (Siegrist, 1987a,b). Siegrist (1987) completed field experiments with replicated test cells installed in silt loam soils that were operated for nearly 6 years. The observed time-dependent loss in infiltration rate (IR_t) was used to develop an empirical model (Siegrist, 1986; Siegrist and Boyle, 1987). The Siegrist model (Siegrist, 1986; 1987s) estimates the relative infiltration rate (infiltration rate at time t as a fraction of the initial infiltration rate at time t_0, or IR_t/IR_0) based on the cumulative mass density loadings of biochemically oxidizable substances and suspended particulates (Fig. 11). Consistent with these findings, field studies of soil absorption systems receiving aerobic unit or sand filter effluent have shown that soil clogging is highly retarded or absent altogether (e.g., Converse and Tyler, 1998).

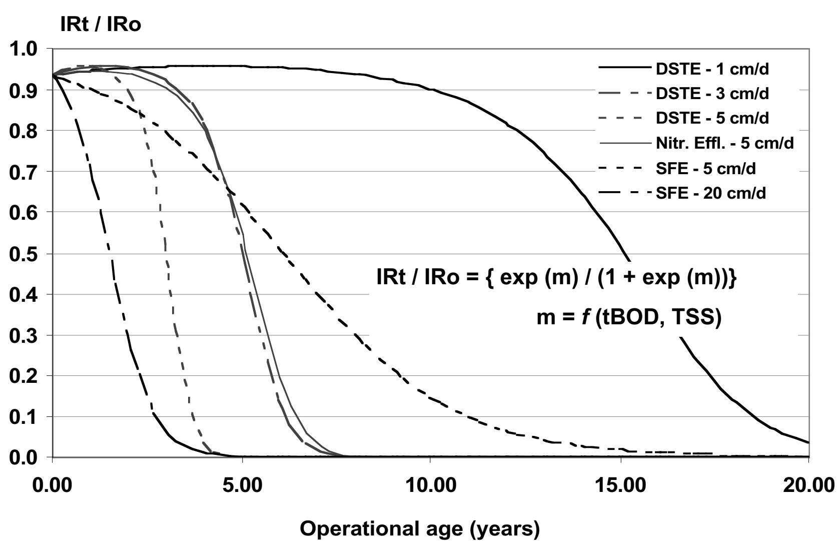

Fig. 11. Illustration of infiltration rate loss in a standard gravel-filled trench based on the cumulative mass density loading of total BOD and suspended solids (kg/m^2) at different hydraulic loading rates and effluent compositions (after Siegrist 1987; Siegrist and Boyle, 1987). (Note: This figure is for illustration purposes only. IRt/IRo values approaching zero do not imply hydraulic dysfunction; also, as IRt/IRo approaches zero and is less than the actual daily loading rate, development of ponding heads up to 30 cm can theoretically increase flux through the infiltrative zone by a factor of 10 to 100 or more depending on clogging zone thickness and resistance).

Slower or absent clogging development with higher quality effluent has led to design approaches that utilize advanced pretreatment (e.g., extended aeration or intermittent sand filtration). This is increasingly being done to enable much higher hydraulic loading rates to be used (10 to 50 cm/d rather than 1 to 5 cm/d) and to reduce the required infiltration area or unsaturated zone thickness. This may be technically sound from an infiltration rate capacity and hydraulic performance basis, but has questionable implications related to purification. While advanced treatment units can reduce BOD_5 and SS loadings and retard wastewater-induced clogging, the concentrations of pathogenic bacteria and virus may not be markedly reduced. Thus absence of a clogging zone may diminish the effective purification of pathogens before ground water recharge. There is no current research that has clearly demonstrated effective pathogen removal in relatively high-rate WSAS with retarded clogging development that are otherwise conventionally designed.

The *method of application*, including the degree of uniformity (on an IS utilization basis) as well as the frequency of application, can influence performance depending the constituent of concern and the type and rate of reactions affecting its removal (see Fig. 12). More frequent application of small doses of STE uniformly applied can yield improved purification with respect to chemical and microbiological constituents (Siegrist and Boyle, 1982; USEPA, 1978; Emerick et al., 1997). This is due to facilitating film flow over particle surfaces and enabling more intimate contact between COC's and media surfaces. As noted below, continuous operation (i.e., year-round) of a WSAS can yield potentially different performance than seasonal or intermittent use, or where long-term resting (e.g., 6 months out of each year) is planned.

The infiltration surface utilization, ISU, is a parameter that describes the fraction of the design or available infiltrative surface that is actually wetted and used for infiltration during operation. The ISU varies from a value at startup (ISUo) to a value at time, t (ISUt) and is a function of the system design including the daily loading rate, the method of application and the hydraulic properties of the natural soil. End members on the ISU continuum (near 0 up to 1.0) include gravity fed systems in high permeability soils (very low ISUo) versus pressure-dosed systems in low permeability soils (very high ISUo). In a mature system that experiences ponding or near-ponding conditions due to clogging development, the ISU approaches 1.0 independent of application method, rate, or soil properties. The ISU is important to treatment as it impacts the flow regime in the vadose zone underlying the infiltrative surface. Two additional related parameters of interest are the HRT and the volumetric utilization efficiency (VUE) of the porous media in the vadose zone beneath the IS. The HRT is important as it determines the time available for reactions to occur. Biochemical treatment reactions such as organic matter degradation, nitrification, and fecal coliform removal can often be described by 1^{st}-order kinetics which relate the concentration at a given depth to that in the applied effluent. The value of the 1^{st}-order reaction rate constant, K , can vary with time and space due to soil clogging development and the accumulation of organic matter and nutrients at the IS and an associated elevated biomass (Nilsson, 1990; Siegrist, 1987a). The rate of reaction for volatilization/sorption/degradation of most constituents is fastest at the infiltrative surface and within the 15 to 30 cm of the vadose zone below it. The purification efficiency predicted by 1^{st}-order reactions is also impacted by the HRT (or t) which is affected by the effluent delivery method and application rate, the soil grain size or pore size distribution, and the degree of soil clogging. Experimental data of Ausland (1998) clearly illustrates the interactions. Ausland completed a series of flow experiments in a large 2-D tank lysimeter (1-m wide by 90-cm deep) using medium vs. coarse sand, point loading vs. uniform distribution, and unclogged, partially clogged, and fully clogged IS conditions. As shown in Fig. 12, the predicted removal efficiencies for unsaturated coarse sand (d_{10}=0.86 mm; d_{60}/d_{10}=1.74) at a daily loading rate of 9.6 cm/d varied from 10% to 100% dependent on conditions. In general, with rate constants on the order of 0.1 to 0.4 hr^{-1} (Ausland 1998), treatment efficiencies of 90% can be achieved with HRT's of 24 hr or less. In research completed by Van Cuyk et al. (2000), four, 3-D lysimeters were studied from startup through nearly one year of operation. Hydraulic and purification behavior was evaluated by routinely monitoring as well as periodic multicomponent surrogate and tracer studies. It was observed that the treatment efficiencies observed in all four lysimeters after the initial 20 weeks of operation were on the order of 90% or higher for COD, ammonium, and fecal coliforms which was not surprising given that the median hydraulic retention times (BT_{50}) were 37 hr or greater. The comparatively lower efficiencies during the first 10 to 20 weeks of operation may be attributed to a lag phase during which initial soil clogging is evolving and active bioprocesses necessary for purification are becoming fully established (e.g., nitrification). McCray et al. (2000) completed model simulations of WSAS showing that soil clogging (base and sidewall) clearly impacts the degree of treatment of certain COC's in the unsaturated zone below the infiltrative surface.

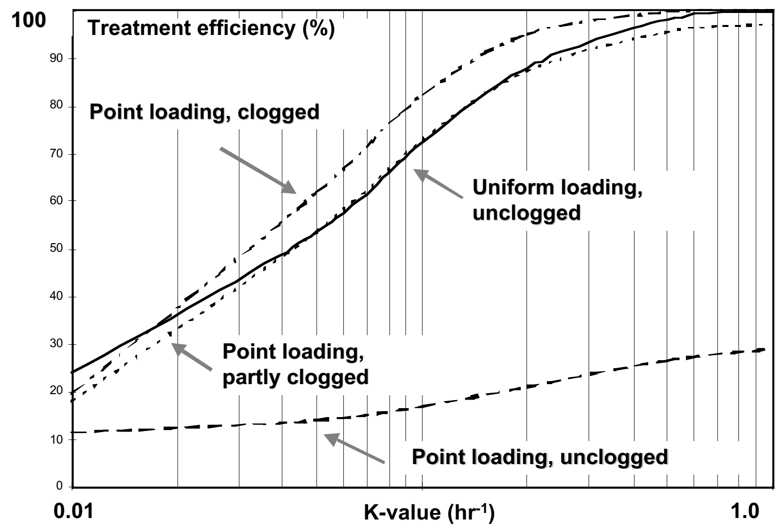

Fig. 12. Purification efficiency as affected by reaction rate and operating conditions which is turn impact hydraulic retention time (after Ausland, 1998).
(Note: data shown are from a 1-m wide by 0.9-m deep, 2-D lysimeter and flow experiments with coarse sand loaded at 9.6 cm/d and Cz/Co = exp(-*K*t), where, Cz = concentration of constituent at depth z from the infiltrative surface, Co = input concentration of constituent at the infiltrative surface, *K* = overall rate constant for combined volatilization/sorption/degradation, and t = hydraulic residence time for percolating water to reach depth z. The rate constant, *K*, is assumed constant with depth).

The volumetric utilization efficiency (VUE) can be defined as the ratio of the volume of media actually contacted by the applied wastewater as compared to the design volume (i.e., the total infiltrative surface area times the media depth) (Van Cuyk et al., 2000). The VUE parameter is directly related to and dependent on the ISU. High VUE's are desirable to enable biofilm and sorption processes, which require adequate surface area contact to achieve a desired removal rate and extent (e.g., phosphorus sorption). In 3-D lysimeter experiments completed by Van Cuyk et al. (2000), the calculated VUE's for week 0 were on the order of 50% hydraulic loading rates and depths that varied by 50% or more. The VUE's at week 8 were nearly 100% suggesting that most of the available horizontal infiltration area was being utilized after an initial two months of early clogging development. Since purification with respect to some constituents such as ammonium and fecal coliforms continued to improve until stabilizing at week 20 or later, it was speculated that there was continued wastewater-induced clogging and a further establishment of purification processes within an operative infiltration zone, rather than an increased expansion of the infiltration area being utilized.

The *depth and geometry of the infiltrative surface* have long been the subject of debate, and to this day, remain poorly understood. Intuitively, shallow placement to exploit the most biogeochemically active zone of the soil profile seems desirable. Narrow trenches that rely on both horizontal and vertically oriented IS areas also appear beneficial. However, very narrow and shallow trenches have limited storage capacity and reduced depth for STE ponding, which may adversely impact long-term hydraulic performance. Other variants include the use of at-grade or mounded systems, the latter being effectively the same as an intermittent sand filter followed by at-grade soil infiltration. An end member incorporating both facets involves the use of drip irrigation in the shallow root zone. All of these systems are often utilized to overcome site conditions that limit the thickness of the unsaturated zone for treatment, such as depth below an IS to a low permeability restrictive layer, seasonal or permanent high ground water table, or shallow bedrock.

The features of the *infiltrative surface interface* can be important to infiltration capacity. The presence of gravel or other media on the surface may reduce the permeability of the infiltration zone due to a variety of factors including (1) deposition of fines that plug pore entries initially or with time, (2) embedment of gravel with the natural soil matrix thereby reducing porosity and permeability, or (3) focusing wastewater organic matter and solids through pore entries that are not plugged or otherwise masked by the gravel. A number of alternatives exist that mitigate the need for gravel within a subsurface infiltration trench or bed. The most common option is a chamber system (Keys, 1996; May, 1996; Tyler et al., 1991) while others are based on fabric-wrapped piping designs.

System size and density of application can affect the system design and performance. As systems become larger and/or the density of application of small systems increases, the potential interaction of wastewater amendment to the landscape needs to be carefully considered. This is due to the hydrologic effects (e.g., mounding) as well as the cumulative pollutant effects and the reduction in assimilative capacity due to simple dilution and dispersion in the ground water. For example, there may be concerns where WSAS application densities are high and they necessarily are located in close proximity to private drinking water wells. Modeling tools (e.g. Table 4) can aid an assessment of the potential cumulative effects and watershed scale concerns associated with WSAS.

<u>4.3.3. WSAS Construction and Operation and Maintenance.</u> *Construction practices* can affect the hydraulic properties of the natural, undisturbed subsurface. These effects include: (1) compaction due to vehicle traffic on the exposed IS or the dumping of gravel aggregate onto it, (2) smearing or puddling of the surface due to shear from a vehicular tire or track at the IS interface, (3) deposition of wind-blown fines while the infiltrative surface is exposed, and (4) smearing and compaction resulting from construction when the soil is too wet (i.e., soil water content exceeds field capacity) (Tyler et al., 1985).

The *age of installation and operational service life* of a WSAS can greatly influence its performance capabilities. The age of installation is important as the state-of-knowledge and standard of practice have evolved over the past 50 years. Systems installed in 1950 are not the same as those installed in 2000. Operational service life combined with age of installation can affect system performance, primarily due to the rate and extent of wastewater-induced clogging. The operation age of a system includes the actual loading rate and continuity of use (i.e., the LF and CF). In general, systems that are loaded near design specifications and used continuously will mature more rapidly in time than those that are underutilized. With operation, wastewater-induced clogging increases the effective area for infiltration and the degree of unsaturated flow conditions in the underlying soil, as well as create a biogeochemically active zone for treatment to occur. Van Cuyk et al. (2000) completed 3-D lysimeter studies to quantify the hydraulic and purification processes during the first year of system operation. Lysimeter results revealed relatively lower hydraulic retention times and vadose zone utilization during the first months of startup with breakthrough of fecal coliforms and MS-2 and PRD-1 viral surrogates in sand WSAS regardless of depth to ground water (60 vs. 90 cm) or infiltrative surface/loading rate scenario (gravel-laden at 5.0 cm/d vs. gravel-free at 8.4 cm/d) (Masson, 1999; Van Cuyk et al., 2000). After 10 months of operation, the percolates were of much higher quality in terms indigenous fecal coliforms (<10 org./100mL) and specific pathogens (non-detect) as well as viral surrogates. Thus, the operational aging process appears quite important to treatment efficiency and raises questions about the treatment performance of WSAS with discontinuous operation (e.g., at seasonal dwellings or with cyclic loading/resting operation).

Operation and maintenance are critical to the performance of a WSAS. If actual conditions such as daily wastewater flow rate or wastewater composition are different than design assumptions then systems can be overloaded and hydraulically fail. Even if the design matches actual conditions, if the WSAS is not properly maintained (e.g., repair of a broken pipe, replacement of a failed pump, periodic pumping of septic tank solids), then dysfunction and failure can result.

4.4. Modeling WSAS Hydraulic and Purification Performance

The performance *capabilities* of wastewater soil absorption systems and the factors affecting them are important, but the ability to *reliably predict* the performance to be achieved under a given set of design and operational conditions is perhaps even more critical. While relatively limited, there are conceptual and mathematical models that specifically relate the performance metrics of a WSAS (e.g., infiltration capacity and soil clogging, purification efficiency, or service life) to site conditions (e.g., soil properties, soil depth, temperature), system design (e.g., IS geometry, depth, or interface character, effluent application rate and composition), and operation (e.g., continuous or discontinuous operation) (see Table 4).

Application of mathematical modeling for describing and predicting performance of WSAS as affected by process design factors and environmental conditions continues to advance with quantitative relationships emerging, being refined, and/or validated including:

$$\text{LTAR} = f\,(\text{clogging zone genesis}), \tag{1}$$

$$\text{CZG} = f\,(\text{HLR, quality and MLR, application method, IS}, K_{sat}, {}^{o}\text{C}, ...)\ , \tag{2}$$

$$\text{ISU} = f\,(\text{IS features, application method, and soil } K_{sat}), \tag{3}$$

$$\text{VUE} = f\,(\text{ISU}), \tag{4}$$

$$\text{Sorption efficiency} = f\,(\text{VUE, media properties, depth}), \text{ and} \tag{5}$$

$$\text{Reaction efficiency} = f\,(\text{kinetics } K, \text{HRT}, {}^{o}\text{C}, ...) \tag{6}$$

where, LTAR = long-term acceptance rate, CZG = clogging zone genesis, HLR = hydraulic loading rate, MLR = mass loading rate, IS = infiltrative surface, K_{sat} = saturated hydraulic conductivity, ISU = infiltrative surface utilization, VUE = volumetric utilization efficiency, K = reaction rate constant, HRT = hydraulic retention time.

While challenging to fully develop and validate, expression of quantitative understanding through mathematical relationships and models can enable effective practice regarding WSAS design and implementation and support development and confidence in performance-based codes. Moreover, such understanding and single-site scale modeling tools are required to properly account for WSAS cumulative impacts, if any, to public health and environmental quality in applications where there are clusters or subdivisions of individual systems. Finally, such knowledge is needed to enable development and allocation of total maximum daily loads (TMDL's) for watershed-scale environmental protection (Chen et al., 1999). Selected modeling tools that have been utilized for onsite WSAS applications as well as a few others that potentially could be adapted are summarized in Table 4.

Table 4. Mathematical models and decision-support tools for design and performance of onsite wastewater soil absorption systems.

Model	Model Type / *Scale*	Developer / Reference	Model description and/or waste related application and results
----	WSAS soil clogging development *Site scale*	Siegrist (1986) Siegrist and Boyle (1987)	Estimates IR_t/IR_o based on cumulative mass loadings of total BOD and suspended solids. Specific results include time-dependent loss in IR results from input of hydraulic loading rate (cm/d) of wastewater flow and concentrations of total BOD (cBOD + nBOD) and SS,
SepTTS	WSAS chemical fate/transport *Site scale*	Lee et al. (1998)	Screening level tool for predicting fate and transport of down-the-drain household chemicals in septic systems.
VIRALT	Well-head protection model for virus *Site scale*	Bechdol et al. (1994)	Bechdol et al. (1992) conducted simulations of ground water in Rhode Island and found that the model was only capable of distinguishing risks between widely different situations. However, coarse textured soils and aquifers common to the coastal watersheds are very susceptible to virus transport. Field monitoring and validation was recommended.
VIRTUS	Virus transport and fate in unsaturated zone *Site-scale*	Yates and Ouyang (1992)	Simultaneously solves eqns. describing transport of water, heat and virus through unsaturated zone of soil. Predictive model of virus fate that allows virus inactivation rate to vary based on soil depth and temperature changes. Tested on datasets in laboratory columns with MS-2 coliphage transport.
----	Bacterial transport *Site-scale*	Harvey and Garabedian (1991)	Bacterial transport in ground water simulated using a colloid filtration model that had been modified to include advection, storage, dispersion and adsorption.
----	Microbial transport *Site-scale*	Teutsch et al. (1991)	One-dimensional model to describe microbial transport that includes decay, growth, filtration and adsorption. During lab-scale tank experiments with MS-2, the predictions closely matched measured results at high flow rates, but did not match at flow rates.
MANAGE	Decision support tool for aquifer vulnerability *Watershed scale*	Kellogg et al. (1997) Loomis et al. (1999) Joubert et al. (1997)	Used to identify ground water pollution sources, future threats, and evaluation effectiveness of various wastewater improvements.
WARMF	Decision support system for TMDL development *Watershed scale*	Chen et al. (1999)	A decision support system to calculate TMDL's for a watershed. Incorporates cumulative effects of onsite systems into pollutant loading as nonpoint sources.
BASINS	Multipurpose environ. analysis system *Watershed scale*	Lahlou et al. (1998)	Used by regional, state, and local agencies in performing watershed-based studies to facilitate examination of environmental information; to support analysis of environmental systems, and to provide a framework for examining management alternatives. Onsite systems can be incorporated as nonpoint sources.
DRASTIC	Ground water sensitivity *Site scale*	Aller et al. (1985) Stark (1997)	Ranking system that evaluates 7 hydrologic factors (depth to water table, aquifer net recharge, aquifer media, soil media, topography, impact of vadose zone, hydraulic conductivity) to yield a numerical index of an area's relative degree of potential for pollution. Has been used to evaluate aquifer sensitivity to nitrate pollution from onsite systems.
3S-NPoP	GIS-based conceptual *Watershed scale*	Stark (1997)	Relates the potential impacts at the source areas to the nitrate levels in the stream, linking septic system site characteristics to water quality.
HYDRUS	Unsaturated flow and solute transport *Site scale*	Simunek et al. (1996) Schwager and Boller (1997) McCray et al. (2000)	Schwager and Boller (1997) Investigated solute and gas transport under intermittent flushing conditions. Found that single flush size and frequency might considerably affect the performance of sand filters by impacting oxygen flux within systems. McCray et al. (2000) simulated 2-D conditions related to flow and transport in WSAS under a range of conditions.
MOFAT	Multi-phase flow and transport code *Site scale*	Kaluarachchi and Parker (1991) Schwager and Boller (1997)	Investigated solute and gas transport under intermittent flushing conditions. Found that single flush size and frequency might considerably affect the performance of sand filters by impacting oxygen flux within systems.
----[2]	(ADI) finite diff. approx. of unsaturated flow *Site Scale*	Ewing et al. (1985)	Studied the effects of unsaturated flow, inflow period length, and horizontal variations in vertical flow rates to determine the design factors having the greatest influence on flow conditions within buried sand filters. Found that application rate, retention times, and depth of the sand filter had the greatest impact on unsaturated flow conditions within the filter medium.
TOPLATS [2]	Nonpoint source *Watershed scale*	Endreny and Wood (1999)	Determines source areas of nonpoint source pollution within a watershed using a water table-driven variable source area (VSA) routine to determine runoff zones. Used for contamination from agricultural land use, but could be used to determine extent of contribution of contaminants from onsite systems.
----	GIS-based *Site scale*	Lasserre et al. (1999)	Models nitrate flux through the unsaturated zone and transport through ground water. Used for contamination from agricultural land use, but could be used for nitrate transport from onsite systems.
FLUNIT [2]	GIS-based *Watershed scale*	Van den Brink et al. (1995)	To evaluate ground water protection strategies based on risk analysis and effectiveness of possible measures. Nitrate concentration changes in the subsurface from agricultural land use sources.
SPARROW [2]	Surface water quality *Watershed scale*	Preston & Brakebill (1999)	Relates in-stream water quality measurement to spatially referenced characteristics of watersheds, including contaminant sources and factors influencing terrestrial and stream transport. Has been applied to nitrogen modeling from point sources, urban areas, fertilizer application, manure generation and atmospheric deposition.
MORELN [2]	Nitrogen cycle *Site scale*	Geng et al. (1996)	Models the nitrogen cycle and nitrate leaching in soil and simulates nitrate migration in an aquifer system. Has been used on agricultural lands.

[1] These models were not developed for wastewater soil absorption systems, but potentially could be adapted to that application.

5. Risk Assessment/Management Applied to Wastewater Soil Absorption Systems

5.1. Risk Assessment and Risk Management Framework

5.1.1. Risk Assessment. Wastewater possesses inherent hazards due to pollutants in it, which can cause adverse effects such as human disease (e.g., due to pathogenic bacteria), or ecosystem upsets (e.g., eutrophication due to nutrient input and fish kills from ammonia input and oxygen depletion). The inherent hazards become a risk when wastewater effluent containing pollutants is hydrologically linked to receptors and the transport/fate processes are not effective in reducing the concentrations at the point of exposure below a threshold which does not cause an adverse response. Formal risk assessment (RA) procedures have evolved from various applications such as organic chemicals and heavy metals in soil and ground water (e.g., Labieniec et al., 1997; Omenn et al., 1997a,b). The general RA process involves characterization of the inherent hazards, the pathways and transport/fate processes, and the routes of exposure and exposure-response properties of the receptor in question (Omenn et al., 1997a,b; Labieniec et al., 1997).

A *site-specific risk assessment* involves a single system comprised of a particular design at a particular location (e.g., classic WSAS for permeable soil conditions at a specific residence). A *generic risk assessment* involves either (1) a population of systems of the same design and location types (e.g., mound wastewater absorption systems for sites with shallow ground water) or (2) a population of different systems distributed at different types of sites within a prescribed space-time domain of interest (e.g., spatial boundaries based on a political jurisdiction such as a county or a hydrologic boundary such as a watershed, and time boundaries for old vs. recent vs. new systems). There is inherent variability and uncertainty in the information regarding site conditions, system design implementation, and system performance as well as the transport/fate to a receptor and the exposure/response characteristics. *Deterministic risk assessments* involve point estimates for the different input parameters, which are then combined to yield an estimate of the risk. Deterministic assessments often employ highly conservative input values for all inputs and as a result, the estimated risk is often highly conservative, and protective of failure in a high percentage (e.g., 99%) of the situations. *Probabilistic risk assessments* utilize distributions for the input parameters, which propagate variability and uncertainty into a distribution of estimated risk. The estimated risk distribution can then be used in risk management decision-making. Formal quantitative risk assessment has rarely been applied to onsite wastewater soil absorption systems (Jones, 2000).

5.1.2. Risk Management. Risk management (RM) involves identifying and choosing between options that might be necessary and appropriate to the mitigate the identified risk to an acceptable level. Risk management options can be addressed at one or more parts of the risk framework from the wastewater source, treatment system design and implementation (which includes engineering design, siting, construction, operation/maintenance), to the pathways and transport/fate processes to exposure points, to the receptors themselves. As noted earlier, performance goals have not been explicitly stated for WSAS. Rather a goal statement might read something like: "A proper WSAS is expected to process all wastewater generated with adequate purification provided by the prescribed system design for a long service life with little O&M." This type of goal statement implies that a properly performing system will successfully process all generated wastewater without seepage of partially treated effluent to the ground surface or back-up of wastewater into a dwelling unit. Moreover, it includes slow percolation through a vadose zone before recharge to a local ground water without causing excessive ground water mounding which could reduce the unsaturated zone depth and adversely affect purification processes.

Performance of WSAS involves both hydraulic and purification function and their interactions (Schwager and Boller, 1997; Van Cuyk et al., 2000). Adequate hydraulic performance can be defined as processing all of the wastewater flow without backing up into the dwelling or seepage to the ground surface. Purification performance can be defined as achieving a given concentration of a COC at a point of assessment. The receiving environment for treated wastewater normally includes the local ground water system, which may be connected to regional ground water systems, and/or surface waters such as rivers, lakes, and estuaries. The sensitivity of the receiving environment to perturbation must be considered.

For risk management, design of a WSAS, whether it be a classic system or one with modifications or an alternative treatment train, should be based on a set of performance goals to mitigate an explicit risk to an acceptable level. For example, a performance goal for the WSAS could be established such that the concentration of NO_3-N in soil solution entering the ground water under a WSAS is below a level where dilution and dispersion in the ground water will reduce the level of NO_3-N at a conceivable point of drinking water extraction does not exceed 10-mg-N/L (the drinking water MCL). In order to design and implement a system or systems to meet that goal requires an understanding of process function and performance with respect to wastewater nitrogen. The design to achieve the goals must account for the natural constraints of a site, the robustness of the WSAS to deviations from design assumptions, as well as the need for and ability to deliver requisite O&M in order to reliably achieve performance capabilities.

5.2. RA/RM for Onsite Wastewater Soil Absorption Systems

Formal risk assessment and risk management have rarely applied to decision-making for onsite systems. However, risk assessment and risk management concepts have been implicit in WSAS practices based on the regulations and code structures controlling their use. Recently explicit risk-based decision-making been advocated (Otis and Anderson, 1994; Hoover et al., 1998a,b; Loomis et al., 1999; Jones, 2000). Most applications of WSAS are based on prescriptive codes (e.g., promulgated at the state level and enforced at the county level) which in turn have been developed based on historical and empirical information which have evolved into a local practice that the contractors in an area are able to accomplish. Modifications have been developed as well as alternative system designs, to enable onsite system use in site conditions that are not suitable for a classic system design. When first introduced, innovations can be permitted for limited use under provisional or experimental programs. Normally an absence of reported problems can lead to a general use approval. In some cases, rigorous monitoring and formal documentation of operation and performance of alternatives have been required or have occurred due to a research interest.

Risk assessment and management concepts implicitly are involved in decision-making for WSAS. For example, most prescriptive codes are designed to constrain WSAS applications to situations where an adverse effect will not occur or be manifested by actions such as:

- Prescribing site conditions that are believed to be suitable for WSAS of a certain design. Site conditions usually involve metrics on landscape position, slope, subsurface permeability and unsaturated soil depth and possibly methods of assessment (e.g., percolation test by a licensed soil analyst),
- Establishing setback distances to points of exposure and receptors, most notably drinking water wells and surface waters,
- Prescribing design features, such as size of a soil absorption unit and related unit operations, and
- Specifying monitoring and assessment methods (usually only for larger systems).

Within the code-based implementation structure, decision-makers still must chose between different system design types and attributes. As shown in Table 5, there are a number of scenarios with WSAS where the risk varies from negligible to high. High risk situations tend to occur where the performance capabilities of the WSAS are deficient or uncertain, and where the environmental situation is sensitive with respect to receptors and exposures. In these and other situations, there are a number of management strategies and options that can be implemented for a given situation and the implicit or explicit risk assessment thereof (Table 6).

Table 5. Example scenarios for wastewater soil absorption systems that pose apparent risks to human health and environmental quality and example risk management options.

Example scenario	Risk characterization	Level of concern and basis	Traditional risk management options	Alternative risk management options
(1) Low density applications of conventional WSAS designs in environmental settings with thin vadose zones of coarse soils or shallow fractured rock and proximal private or public drinking water wells.	Health risk to residents due to ingestion of drinking water containing nitrates and pathogens, and to visitors from pathogens.	Moderate due to inherent treatment limitations of conventional WSAS under the environmental conditions.	o Holding tanks o Prohibit development	o Alternative WSAS designs (e.g.,. mounds) o Advanced treatment before conventional WSAS
(2) High density applications of conventional WSAS designs in environmental settings with thin vadose zones of coarse soils or shallow fractured rock and proximal private or public drinking water wells.	Public health risk due to ingestion of drinking water containing nitrates and pathogens	High due to inherent treatment limitations of conventional WSAS under the environmental conditions and the multiple sources contributing.	o Provide public water from a safe source o Provide sewers and a central treatment plant	o Alternative WSAS designs (e.g.,. mounds) o Advanced treatment before conventional WSAS
(3) Low or high density applications of WSAS on landscapes and soils with low permeability and seasonal saturation or flooding.	Health risk to residents, neighbors and visitors due to seepage to the ground surface and direct or indirect contact and ingestion or inhalation of pathogens.	High due to uncertainty in design and performance relationships for conventional WSAS under the environmental conditions.	o Accept intermittent seepage o Increase septic pump out during wet periods o Increase WSAS size	o Alternative WSAS designs (e.g., mounds) o Advanced treatment before conventional WSAS o Advanced treatment and disinfection for surface discharge
(4) Cesspools and old seepage pits located on the shores of sensitive receiving waters such as lakes and estuaries.	Environmental risk to ecosystem including degradation of water quality and biota habitat.	High due to inherent limitations of treatment under conditions.	o Provide sewers and central treatment plant	o Upgrade existing onsite systems with advanced treatment or alternative WSAS designs.
(5) WSAS that are seasonally used and do not develop adequate soil clogging and biofilm growth to achieve treatment for pathogens.	Health risk to residents, neighbors and visitors due to drinking water ingestion of drinking water from wells contaminated by pathogens.	High due to uncertainty about treatment in seasonally used systems.	o None since not recognized	o To be determined
(6) WSAS that are designed for higher LTAR's based on advanced treatment units that reduce BOD and SS and thereby retard soil clogging.	Health risk to residents, neighbors and visitors due to drinking water ingestion of drinking water from wells contaminated by pathogens.	High due to uncertainty about treatment of pathogens in WSAS receiving advanced treatment unit effluent.	o None since not recognized	o To be determined

Table 6. Example risk management strategies and options for wastewater soil absorption systems at the site-scale and watershed scales.

Risk management strategy	Example option	Desired impact(s) or effect(s) of option	Availability and implementability of option	Implementation & reliability of option	Impact if option fails or has a dysfunction
1. Conventional WSAS design and implementation	A. Conventional narrow trench design (e.g., narrow trenches with shallow placement)	Control flux of pollutants into ground water while treating all wastewater generated without seepage to ground surface or backup into dwelling	Design and product based options that are widely available May be constrained by site and/or environmental conditions	Design, installation and operation by trained practitioners	Excessive risk to receptors dependent on site and possibly watershed conditions
2. Source control	A. Remove toilet waste and treat graywater by soil absorption (e.g., compost toilet)	Reduce pollutant loading to WSAS, particularly N and pathogens	Product and/or engineered option Commercially available	Good unless toilet waste system (e.g., compost toilet) is circumvented by user	Loss of effect on specific pollutant loadings plus system hydraulic overloading
3. Modified or alternative WSAS design and implementation	A. Increased conservatism in design and operation (e.g., reduce loading rate from 4 to 2 cm/d)	Reduce soil hydraulic application rate; or increase vadose depth;	Engineering option May be constrained by lot size, environmental conditions, and/or cost	Design and installation by individuals/firms normally involved in onsite systems	Loss of safety factor with default back to performance of conventionally designed system (1A).
	B. Alternative soil absorption system designs (e.g., at-grade or mound systems or drip irrigation)	Increase vadose zone depth; increase chance of nutrient removal	Engineering option May be constrained by lot size, environmental conditions, local competency, and/or cost	Requires design and installation by trained professional or reliability is poor	Excessive risk to receptors dependent on site and possibly watershed conditions
	C. Advanced treatment before soil absorption (e.g., sand filtration but not disinfection)	Reduce pollutant loading to WSAS, particularly tBOD, TSS, N	Product and/or engineering option May be constrained by local competency, and/or cost	Requires O&M by trained professional or reliability is poor	Increased pollutant loadings to WSAS with potential for hydraulic and purification dysfunction and increased risk to receptors
	D. Advanced treatment before soil absorption (e.g., sand filtration with UV disinfection)	Reduce pollutant loading to WSAS, particularly tBOD, TSS, N and pathogens	Product and/or engineering option May be constrained by local competency, and/or cost	Requires O&M by trained professional or reliability is poor	Increased pollutant loadings to WSAS with potential for hydraulic and purification dysfunction and increased risk to receptors
4. Land use and exposure/receptor controls	A. Separation and setback distances (e.g., 200 ft. to drinking water well rather than 100 ft.)	Increase separation to receptors to enable dilution/ dispersion/ reactions to reduce exposure concentrations	Requires ability to model and predict environmental transport/fate and exposure benefits of increased separation	Requires site characterization and land use data and modeling expertise	If predictions are inaccurate desired benefits on exposure concentrations will not be realized and risks will be higher than predicted
	B. Increased lot size or reduced density of application (e.g., reduce density from 4 DU/acre to 0.5 DU/acre)	Reduce cumulative effects to receiving environment and enable dilution/ dispersion/ reactions to reduce exposure concentrations	Requires ability to model and predict environmental transport/fate and exposure benefits of reduced density	Requires site characterization and land use data and modeling expertise	If predictions are inaccurate desired benefits on exposure concentrations will not be realized and risks will be higher than predicted
5. Monitoring	A. Monitoring (e.g., pump and level sensors, vadose lysimeters, ground water wells)	Detect dysfunction and implement corrective action before an adverse effect occurs	Hydromechanical functions can be readily monitored but purification and subsurface conditions are difficult and costly	Design, installation and also telemetric and/or onsite sampling/analysis by trained professional	Missed dysfunction and effects could occur and be undetected

6. Critical Questions and Research Needs

6.1. Questions and Areas of Research Need

Despite a history of use and a considerable body of research and observations from practical experiences, further research is needed to support the long-term, effective use of onsite and decentralized WSAS. A nationally coordinated program of research is needed to produce an enhanced understanding of WSAS hydraulic and purification processes and their complex interactions including the effects of design, operational and environmental factors. Key questions remain at the site-scale up to the multiple-site to watershed scale. Table 7 provides a listing of research questions, while some additional remarks are given below.

- Almost all of the research needs related to WSAS have an underlying common theme: there is a need for quantitative understanding that enables rational process design and performance relationships to be modeled for predictive purposes. This is critical to our ability to move beyond empirical studies that provide information that is highly constrained to the soil and site conditions, design and operational factors, and environmental conditions of the particular study in which the data were generated. Experimental work needs to appropriately span reasonable space and time scales and incorporate modeling facets to help provide the needed insight into WSAS processes and performance and rationale methods of design and implementation. The WSAS field needs quantitative relationships and validated models and decision-support tools.

- Basic research is needed to understand clogging zone genesis and performance effects. Clogging zones are dynamic biogeochemical zones, the characteristics of which can be affected by design factors (e.g., wastewater pretreatment and loading rate, application method, IS geometry and features) and environmental conditions (e.g., soil pore size distribution, soil organic content and pH, soil wetness and temperature, soil microbial biomass and diversity). The clogging zone is known to be extremely important to hydraulic and purification processes in WSAS and there is some understanding of its time-dependent development based on composition and loading rate as well as some of its physical/chemical and microbiological properties. However, further understanding is required. In particular, it is critical to understand the role of clogging zones in reliably achieving high degrees of removal and die-off/inactivation of pathogens (bacteria and virus) both within the clogging zone itself or the underlying unsaturated soil. Application of modern environmental chemistry methods and molecular biology tools and approaches may greatly aid elucidation of the underlying processes and their effects.

- The understanding of clogging zone development must be translated into a workable design practice for WSAS including support for prescriptive- and performance-based codes.

- The complex relationships of IS features and geometry, wastewater composition and loading rate, and the method of wastewater delivery and application, and their effects on the rate and extent of soil clogging and the hydraulic and purification performance of WSAS needs to be elucidated. Fundamental information would enable rational design choices in areas such as sidewall vs. bottom IS area, open vs. aggregate-laden surfaces, shallow vs. deep placement, gravity vs. dosed application, dosed vs. pressure-dosed delivery, and uniform vs. serially loading.

- Research is needed to fully understand the effects of unsaturated zone depth including the effects of transient operational or environmental conditions, on WSAS performance. For example, seasonal saturation that reduces the vadose zone depth may temporarily reduce treatment efficiency, but over the life of the system it may not be consequential from a risk perspective. Also, seasonal fluctuations in soil temperature, moisture potential, and aeration are of concern with respect to their effects on microbial transport.

- o Site evaluation practices and their translation into WSAS design need refinement. The use of the percolation test continues despite compelling evidence that it is subject to huge errors and the values measured (MPI) have no fundamental relationship with flow processes in new or mature WSAS.

- o Operational discontinuity including planned periodic resting or random intermittent or seasonal use may have benefits with respect to retarding clogging development, but it may conversely have adverse effects on purification. Research is needed to understand operational discontinuity effects on clogging zone development or degradation once present, and the effects on purification of pathogens.

- o Reviews and studies to date have not been extensive, but they do suggest there is very little concern over heavy metals and organic chemicals (e.g., petrochemicals and chlorocarbons) in domestic septic tank effluent. However, there may be other chemicals of concern such as endocrine disruptors from contraceptives or other products used in dwellings and these warrant some investigation.

- o There are a range of modifications and alternatives to classic system designs and in many cases an absence of fundamental understanding. Some of these don't entail great cost nor cause harm if they fail to perform at a claimed level and thus decisions regarding their use are not complex. However, some approaches or technologies can pose a cost-benefit decision and even a risk consequence if dysfunction or failure occurs. Thus, performance and benefit/cost data are needed for AOU's.

- o Knowing more about the underlying processes in WSAS and their effects on treatment (as described above) would enable definition of critical parameters that could be used for assessment of operational state and performance. With such parameters defined and if there were reliable methods to monitor for critical assessment parameters and even communicate this information using telemetry, system performance could be tracked, dysfunctions detected early, and failures or serious adverse effects prevented. While hydromechanical functions can be monitored successfully at this time, there remain problems with the necessary strategies for and methods to be used regarding bacteria and virus.

- o The correct measures of system performance that provide a desired risk reduction must be defined and the means by which the requisite measures can be made, both cost-effectively and reliably, needs to be determined. There is also a need to develop effective and efficient monitoring and measurement methods that can be used to identify and diagnose WSAS operation and performance status. Such an understanding would enable diagnostic strategies for identifying individual systems within a cluster or community that are in need of upgrading or replacement.

- o At the multiple site to water shed scale of applications, there is a great need for information on the impact of onsite WSAS on surface and ground water quality. Decision-makers are confronted by continuing debates over questions such as how to establish minimum lot sizes, how to determine and defend setback distances, discriminating out the WSAS contributions of nutrients and pathogens to receiving waters (drinking water wells, bathing lakes, etc.), and so forth. Moreover, with continuing concerns and resulting drinking water regulations (e.g., source water protection and ground water disinfection) as well as the establishment of TMDL's for watersheds, there will be an increasing need for understanding as well as models and decision-support tools that are applicable, process-based, and readily useable for the multiple site up to watershed scale applications.

- o National, integrated studies using systematic state-of-the-art methods needs to be completed to define the hydraulic and purification performance of classic, modified and alternative systems under a range of conditions. This study could be completed by a multi-institutional team that has access to and use of demonstration projects and test facilities located in many parts of the U.S. Such study could include design and implementation process review, installation and operation records review, onsite inspections, sampling and analysis, and microbial surrogate/chemical tracer testing.

6.2. Prioritization of Research Needs

Prioritization of the various research needs was completed by the authors of this white paper using a multi-criteria, weighted evaluation scheme (e.g., Kepner and Tregoe, 1973). Five attributes were identified as important to assessing the priority of a research need and a weight was assigned to each. These included: (A) level of current science and technology understanding (wt. = 0.3), (B) level of importance to design and performance of new WSAS (wt. = 0.2), (C) impact if the research is completed and the need is satisfied (wt. = 0.3), (D) feasibility and cost of completing the work (wt. = 0.1), and (E) known or suspected work already in progress (wt. = 0.1). Before scoring the various needs listed in Table 7, some were first combined with other closely related needs. Then for each of the research needs, each attribute (A to E) was considered and given a numerical score of 1, 3 or 5 points based on explicit metrics (see Table 8). The weighted summary score was finally computed for each research need yielding the results shown in Table 8. The needs were then ranked in four priority groups (i.e., very high, high, moderate, and low). This group ranking was based on similarity of scores between research needs and the breakpoints in the numerical ranking.

7. Conclusions

Onsite and decentralized wastewater treatment in the U.S. relies on subsurface infiltration and percolation through the unsaturated zone prior to ground water recharge. These systems have evolved during the 20th century from early designs that were focused on simple disposal to contemporary designs that are intended to achieve advanced treatment. While the experience base does not suggest serious or broad-based problems with recent or current WSAS practices, it also does not demonstrate consistently adequate performance based on an established design and implementation understanding. Moreover, it is possible that WSAS technology is not being exploited fully and/or as effectively as it might, or alternatively, inappropriate and deficient applications may be evolving. There is a considerable knowledge base regarding WSAS design, implementation, and performance, that enables most systems to be protective of public health and environmental quality. However, understanding is not fundamental enough to discriminate between different approaches to WSAS system design and implementation, such that rational decision-making will lead to the most cost-effective approach for reducing risk to an acceptable level. Of the many research needs identified, several are given high priority because of their judged importance. As shown in Table 8, high and very high priority research needs include those that support: (1) fundamental understanding of clogging zone genesis and unsaturated zone dynamics and their effects on treatment efficiency, particularly pathogenic bacteria and virus, (2) development of modeling tools for predicting WSAS function and performance as affected by design and environmental conditions, (3) identification of indicators of performance and methods of cost-effective monitoring, and (4) development of valid accelerated testing methods for evaluating long-term WSAS performance.

Table 7. Research questions for wastewater soil absorption systems. [1]

Strategic focus	Tasks	Products	Uses
I. Function and Design Needs			
1. What is the effect of pretreatment on soil clogging zone genesis and WSAS hydraulic and purification performance?	A. Conduct experiments with instrumented WSAS systems of the same total size but with optional levels of pretreatment such as (1) domestic STE, (2) graywater STE, (3) sand filter effluent, and (4) aerobic unit effluent, and define IRt / IRo and pollutant fluxes through a given depth of unsaturated soil over time. Utilize surrogate/tracer testing to also assess treatment potential for virus and other non-routine constituents of concern.	1. Quantitative data and empirical and/or mechanistic models for LTAR's and treatment efficiency. 2. Relationship of unsaturated soil depth to treatment efficiency for different soil systems with different degrees of soil clogging.	(a) Support design of specific systems and development of performance and prescriptive code requirements. (b) Provide input for cumulative effects and watershed scale assessment models. (c) Support decisions regarding use of advanced pretreatment with higher application rates under otherwise comparable design and site conditions.
	B. Conduct experiments to assess pathogen purification as affected by clogging zone biogeochemical activity levels as a function of pretreatment level, temperature, and operational age. Apply advances in environmental chemistry, microbiology and biotech molecular methods to understand fundamental nature of WSAS and cause/effect relationships.	1. Information on the role and importance of the clogging zone to pathogen purification (especially virus) and public health protection.	
2. What is the relationship of infiltrative surface character on short- and long-term hydraulic properties of the infiltrative surface zone?	A. Conduct factorial designed experiments to explore the main and interaction effects of (1) vertical vs. horizontal surfaces and (2) gravel vs. gravel free surfaces, on infiltration capacity over time and pollutant fluxes in the underlying vadose zone.	1. Information on the relative behavior of different infiltrative surface features on infiltrability and LTAR's and pollutant fluxes to ground water.	(a) Support design to achieve optimum LTAR's without compromising treatment efficiency.
3. What is the relationship between clogging zone genesis and the resultant loss in infiltration rate over time with common STE WSAS design, operation, and environmental factors?	A. Conduct factorial designed experiments to evaluate the effects and interactions of (1) hydraulic loading rate, (2) application method, (3) infiltrative surface character, (4) soil texture/structure, (5) soil temperature, and (6) soil moisture conditions, on development of an LTAR.	1. Semi-quantitative and quantitative data and process models that describe infiltrative surface utilization and volumetric utilization efficiency with time and the HRT within the soil.	(a) Predict ISU, VUE, and HRT, which can be used to predict treatment efficiency.
4. What is the treatment efficiency achieved in a WSAS designed with different methods of application of domestic STE?	A. Conduct experiments with instrumented WSAS systems of the same size but with optional methods of delivery and distribution including (1) gravity/trickle, (2) serial loading, (3) dosed, and (4) pressurized uniform distribution. Identify pollutant fluxes through a given depth of soil over time.	1. Quantitative data on pollutant fluxes through a given depth of unsaturated soil over time.	(a) Provide information for use in prescriptive codes. (b) Support performance-based design.
5. For a population of similar WSAS in a similar environmental setting, what is the time-dependent relationship between performance and age of operation (a.k.a., service life)?	A. Survey large populations of systems with stratified random sampling methods to assess hydraulic performance and develop % functioning vs. age of operation relationships.	1. Fraction functioning vs. age of operation curves for different WSAS designs in different environmental settings.	(a) Support benefit/cost analyses of decentralized vs. centralized systems. (b) Input for performance guarantees, inspection, and certification programs.
6. How is treatment efficiency affected by transient and extreme environmental conditions?	A. Conduct monitoring and experiments of treatment efficiency as affected by ephemeral or seasonal saturation in the vadose zone beneath a WSAS.	1. Information on the adverse effects if any of ephemeral or seasonal saturation in the vadose zone beneath a WSAS.	(a) Provide basis for design for common but challenging conditions.
	B. Conduct monitoring and experiments of treatment efficiency as affected by very low and very high soil temperatures.	1. Information on the temperature dependency of WSAS function.	
7. What models are appropriate for predicting treatment efficiency as a function of siting, design, and operation?	A. Utilize databases produced by experimental work (I.1 to I.6) to support model development and validation for application at the single site to multiple site and watershed scales.	1. Modeling tools for screening level assessments to quantitative prediction of performance.	(a) Provide information for use in prescriptive codes. (b) Support performance designs. (c) Enable cumulative effects assessment and TMDL allocations.
	B. Develop a methodology for evaluating the degree of model complexity required for a given decision-making situations.	1. Decision-logic for selecting one modeling approach over another in a given situation.	

Table 7. cont. Research questions for wastewater soil absorption systems. [1]

Strategic focus	Tasks	Products	Uses
II. Site Evaluation Needs			
1. What is the relationship between natural soil profile properties and the hydraulic capacity of a single site? Alternatively stated, what are the essential field data needed to support understanding and/or modeling of unsaturated flow and hydraulic capacity?	A. Develop methods to directly measure the soil pore size distribution at the local-scale and based on scaling theory, estimate the relevant site-scale value.	1. Methods and apparatus to directly estimate pore size distribution.	(a) Input to models on water and gas flow and pollutant transport in the vadose zone beneath a WSAS. (b) Support siting and design including landscape loading effects on degree of saturation and ground water mounding.
	B. Develop relationships between morphology and indirect measures (e.g., penetration resistance) with pore size distribution in different soil environments.	1. Methods and apparatus to indirectly estimate pore size distribution.	
	C. Develop methods and apparatus to enable a more accurate calculation of hydraulic conductivity and capacity of low permeability soils and soils that have shallow ground water tables.	1. Apparatus and methods for determining hydraulic conductivity properties in low permeability media.	
2. What methods can be used to assess the hydraulic capacity of a site for larger and clustered WSAS applications?	A. Evaluate existing hydrologic assessment approaches (e.g., for spatial variability and heterogeneity), field techniques (e.g., geophysical methods), and modeling tools for their applicability and reliability for WSAS applications.	1. Approach to assessment and list of applicable assessment and modeling tools.	(a) Evaluate sites and develop landscape configurations for WSAS to avoid exceeding site capacity.
3. How can the natural soil properties that impact wastewater-induced soil clogging development be assessed in the field during site evaluation?	A. Utilize experimental data generated in I.3.A. to assess impact and relationship of soil properties to design application rates and LTAR.	1. Matrix of soil properties and appropriate design application rates.	(a) Support rational sizing of infiltrative surfaces.
4. What methods can be applied to assess the treatment capacity of a site for nutrients, bacteria and virus?	A. Develop and validate testing techniques that can reliably measure the effectiveness of a given profile for treatment of key constituents of concern.	1. Test methods for assessing treatment effectiveness.	(a) Support system design for a given treatment objective. (b) Provide more accurate methods to assess site capacity and treatment capabilities. (c) Input to flow and transport models for treatment efficiency.
5. What methods can be used to estimate the contribution of existing or new WSAS to pollutant loads in a watershed or sub-watershed?	A. Utilize modeling and decision-support tools produced from I.7.	1. Modeling tools for screening level assessments to quantitative prediction of performance.	(a) Enable assessment of cumulative effects (b) Enable explicit incorporation of WSAS in TMDL assessment and allocations.

Table 7. cont. Research questions for wastewater soil absorption systems. [1]

Strategic focus	Tasks	Products	Uses
III. Performance Monitoring Needs			
1. What is an appropriate methodology for defining the space-time domain for evaluating performance of one or many WSAS, that is protective of public health and environmental quality in a given setting?	A. Develop a paradigm for the WSAS as a treatment unit and what the appropriate space and time dimensions are within the context of public health and environmental receptors and risks.	1. Improved performance monitoring approaches that enable risk assessment and management.	(a) Support development and application of permits and monitoring approaches to verify compliance.
2. What are easily measured "indicators" of WSAS function that can be used to predict treatment performance?	A. Based on system function, identify key indicators, and test those indicators under varied conditions.	1. Information on readily measured system functional attributes that are indicative of treatment performance.	(a) Support application of relatively cheap and reliable monitoring and performance assessment methods.
	B. Conduct studies to develop correlations between percolate fluxes estimated from analysis of soil solids versus soil solution for nutrients, bacteria and virus.	1. Statistical relationships for alternative sampling and analysis approaches (e.g., soil coring vs. soil solution sampling for N, P, fecal bacteria, virus).	
	C. Conduct studies to determine the utility and reliability of online monitoring of water quality (air composition) indicators (e.g., pH, Ec, D.O.) and treatment performance.	1. Statistical relationships for indicators vs. treatment parameters in WSAS.	
3. What methods can be reliably used to provide data on purification performance and the flux of pollutants, particularly bacteria and virus, from a WSAS into an underlying ground water?	A. Conduct studies of methods and statistical data analysis approaches for monitoring in the vadose zone and ground water beneath single systems and small clusters of systems.	1. Methods and apparatus for monitoring and performance assessment for single sites and small clusters.	(a) Monitoring of existing and new systems suspected to have poor or inadequate treatment to target upgrade or replacement needs.
	B. Conduct studies of methods and statistical data analysis approaches for monitoring in the vadose zone and ground water for larger developments and watersheds. Carryout out field testing to validate viability and utility of methods and approaches.	1. Methods and apparatus for monitoring and performance assessment for cumulative effects in larger developments and watersheds.	(b) Routine monitoring of WSAS to verify compliance with permits.
	C. Conduct controlled studies to determine the nature and reliability of the correlation between fecal coliforms and pathogens (infectious bacteria and enterovirus), and assess the validity of fecal coliforms as an indicator.	1. Information on the validity of fecal coliforms as an indicator of pathogen treatment in WSAS.	(c) Monitoring of WSAS to verify pollutant allocations made as part of TMDL's in a watershed.
4. What methods are available to assess the treatment performance directly or by estimation, of old WSAS of unknown design and installation, and operational history?	A. Test methods and approaches developed in III.1 to III.3 at old systems in different environmental settings.	1. Methods and apparatus for monitoring and performance assessment for old unknown WSAS.	(a) Monitoring of existing and new systems suspected to have poor or inadequate treatment to target upgrade or replacement needs.
5. What is the role and impact of remote sensing and monitoring on performance assurance for decentralized systems?	A. Conduct studies of cost/benefit of remote sensing and SCADA technology for controlling and monitoring WSAS function and performance.	1. Information on available methods, costs, and viability.	(a) Provide information to support development of contract services in the private and public sectors. (b) Enables performance-based design and implementation.

Table 7. cont. Research questions for wastewater soil absorption systems. [1]

Strategic focus	Tasks	Products	Uses
IV. Other Supporting Needs			
1. What is the composition of the effluent produced by different types of emerging tank-based treatment units?	A. Complete monitoring of test systems or full-scale installations to define effluent concentration distributions for key constituents in the effluent from different treatment units such as (1) add-on units to septic tank, (2) spin-disk filters, (3) foam and textile filters, (4) peat filters, (5) LECA filters, and (6) aerobic package plants. Key constituents include those that affect soil clogging development (e.g., tBOD and SS) and also constituents of public health and environmental quality concern.	1. Information on the effluent composition characteristics (central tendency and spread of concentrations) and reliability of alternative pretreatment units as compared to septic tank treatment prior to WSAS.	(a) Provide input to analysis of effects of pretreatment on soil clogging and performance effects. (b) Provide input to risk reductions afforded by increased pretreatment prior to WSAS.
2. What is the composition of the effluent produced by different types of emerging tank-based treatment units?	A. Conduct international literature review and if needed, complete monitoring of source separation systems.	1. Information on the effluent composition characteristics (central tendency and spread of concentrations) and reliability of source separation to produce a stated quality of effluent (e.g., graywater STE) prior to WSAS.	(a) Provide information on the benefits and reliability of source separation to achieve pollutant mass reductions and risk reductions therefrom.
3. What methods can be used to restore the infiltrative capacity of a WSAS with excessive wastewater-induced soil clogging?	A. Conduct studies of alternative approaches based on knowledge of soil clogging genesis such as (1) long-term resting, (2) improved pretreatment, (3) forced aeration, (4) physical disruption, and (5) chemical amendments.	1. Methods and equipment to restore excessively clogged WSAS such as occurs with very old, overused, or commercial systems.	(a) Restore dysfunctioning WSAS and mitigate adverse health effects due to exposure to partially or untreated wastewater.
	B. Develop a methodology to diagnose WSAS function and performance dysfunctions and select the most effective restoration technique.	2. Information and methods for assessing hydraulic dysfunction and choosing a restoration technique.	(a) Support continued use of WSAS and prevent unnecessary replacement of systems at higher cost and disruption compared to that of restoration.
4. What short-term tests can be used to predict long-term performance?	A. Conduct comparative experiments with accelerated loading schemes and based on findings, evaluate implications of time scales on testing of new technologies.	1. Practical test procedures that allow short-term testing of technologies with long functional service lives	(a) Test protocols for evaluating WSAS system performance to satisfy regulatory demands and/or certification programs
5. What improvements in performance of WSAS can be attributed to training and certification programs?	A. Conduct studies to evaluate the improvements in performance that have occurred and can be attributed to training and certification programs.	1. Information on value and need for training and certification programs.	(a) Support state and local decisions regarding training and certification programs.

[1] Research needs for WSAS as outlined in Table 7 were intentionally developed to exclude the facets of implementation such as education and training, materials and construction quality, regulatory/certification programs, system management, septage management, and so forth. While these are recognized as important and relevant to WSAS design and performance, but beyond the scope of this research needs white paper.

Table 8. Prioritization of research questions into ranked research needs.

Research question and need		Attribute score[1]					Weight. score[1]					Total	Rank by	Priority	Comments
No.	Description	A	B	C	D	E	A 0.3	B 0.2	C 0.3	D 0.1	E 0.1	score	score[2]	group[3]	
I.1.A.	Effect of pretreatment IRt/IRo and fluxes	3	3	5	3	5	0.9	0.6	1.5	0.3	0.5	3.80	6	H	
I.1.B.	Pathogen fate vs. soil clogging genesis	5	5	5	5	3	1.5	1.0	1.5	0.5	0.3	4.80	1	VH	
I.2.A.	I.S. character and hydraulics	3	5	3	3	3	0.9	1.0	0.9	0.3	0.3	3.40	13	M	Needs I.2.A., I.3.A., and I.4.A. are related and were grouped for ranking
I.3.A.	Effects/interactions of STE on LTAR														
I.4.A.	Effects of application methods on trtment														
I.5.A.	Survey large populations for service life	5	3	1	3	5	1.5	0.6	0.3	0.3	0.5	3.20	16	M	
I.6.A.	Treatment effects of seasonal saturation	3	3	3	3	5	0.9	0.6	0.9	0.3	0.5	3.20	16	M	Needs I.6.A. and I.6.B. are related and were grouped for ranking
I.6.B.	Treatment effects of temp. extremes														
I.7.A.	Model development from databases	5	5	3	5	3	1.5	1.0	0.9	0.5	0.3	4.20	4	VH	Needs I.7.A. and I.7.B. are related and were grouped for ranking
I.7.B.	Develop methodology for model selection														
II.1.A.	Methods to directly measure pore size	3	3	1	5	3	0.9	0.6	0.3	0.5	0.3	2.60	19	L	Needs II.1.A., II.1.B., and II.1.C. are related and were grouped for ranking
II.1.B.	Methods to indirectly estimate pore sizes														
II.1.C.	Hydraulic cap. of LPM and shallow soils														
II.2.A.	Evaluate hydro assessment methods/tech.	3	5	3	5	3	0.9	1.0	0.9	0.5	0.3	3.60	8	H	
II.3.A.	Field assessment of soil effects on LTAR	3	5	1	3	3	0.9	1.0	0.3	0.3	0.3	2.80	18	L	
II.4.A.	Testing techniques for treatment potential	3	5	3	5	3	0.9	1.0	0.9	0.5	0.3	3.60	8	H	
II.5.A.	Estimate pollutants loads to watersheds	3	5	3	3	3	0.9	1.0	0.9	0.3	0.3	3.40	13	M	
III.1.A.	Paradigm for WSAS treatment unit	5	5	1	5	5	1.5	1.0	0.3	0.5	0.5	3.80	6	H	
III.2.A.	Key indicators of system function	3	5	3	5	3	0.9	1.0	0.9	0.5	0.3	3.60	8	H	Needs III.2.A., III.2.B., and III.2.C. are related and were grouped for ranking
III.2.B.	Correlation’s for solids vs. percolate														
III.2.C.	Utility of online water quality sensors														
III.3.A.	Monitoring of VZ/GW for small appl.	3	5	3	5	1	0.9	1.0	0.9	0.5	0.1	3.40	12	M	Needs III.3.A. and III.3.B. are related and were grouped for ranking
III.3.B.	Monitoring of VZ/GW for larger appl.														
III.3.C.	Correlation’s of FC and pathogens for WSAS	5	5	3	5	3	1.5	1.0	0.9	0.5	0.3	4.20	4	VH	
III.4.A.	Test methods for old systems	5	1	3	3	5	1.5	0.2	0.9	0.3	0.5	3.40	13	M	
III.5.A.	Cost/benefit of remote sensing/SCADA	5	5	3	5	5	1.5	1.0	0.9	0.5	0.5	4.40	3	H	
IV.1.A.	ATU effluent profiles	3	3	1	3	3	0.9	0.6	0.3	0.3	0.3	2.40	21	L	
IV.2.A.	Source separation systems lit review / mon.	3	3	1	5	3	0.9	0.6	0.3	0.5	0.3	2.60	19	L	
IV.3.A.	Restoration of clogged systems	3	1	1	3	5	0.9	0.2	0.3	0.3	0.5	2.20	22	L	Needs IV.3.A. and IV.3.B. are related and were grouped for ranking
IV.3.B.	WSAS performance dysfunction diagnoses														
IV.4.A.	Accelerated loading testing	5	5	5	3	3	1.5	1.0	1.5	0.3	0.3	4.60	2	VH	
IV.5.A.	Performance benefits of training/certif.	3	5	3	3	5	0.9	1.0	0.9	0.3	0.5	3.60	8	H	

[1] Prioritization categories and attributes with points: Total score = sum{(wt.A)(A) + (wt.B)(B) + (wt.C)(C) + (wt.D)(D) + (wt.E)(E)}

A = Level of current science and technology base (wt. = 0.3)

1 = Mechanistic understanding exists; 3 = Empirical data exists for WSAS under common conditions or relevant understanding in allied fields; 5 = Limited/qualitative understanding exists for a few conditions.

B = Level of importance to design and performance of "new" WSAS (wt. = 0.2)

1 = Not very critical, confirms expected/likely performance with more data; 3 = Enables semiquantitative design/analysis; 5 = Enables rational design and/or performance assessment.

C = Impact if research is completed and need is satisfied (wt. 0.3)

1 = No extension or use or risk reduction for current applications likely; 3 = Reduces risk uncertainty regarding WSAS uses; 5 = Enables WSAS applications under new situations with known risk.

D = Feasibility and cost of completing work (wt. = 0.1)

1 = Uncertain and/or very high cost; 3 = Can surely be done but at mod. to high cost; 5 = Has been / can be done at low cost and/or has been done in other fields and can be applied to WSAS with leverage.

E = Known or suspected work in progress (wt. = 0.1)

1 = Programs or projects ongoing that should produce needed results; 3 = Programs or projects ongoing that should produce part of needed results; 5 = No known programs ongoing or pending.

[2] Numerical ranking is based on weighted attribute scoring with the highest weighted score yielding the highest rank in terms of priority of research need.

[3] Ranking into four groups is based on similarity of scores \ and breakpoints in the numerical ranking: Very high (VH) = $\geq$4.0; High (H) = 3.5 to 3.9; Moderate (M) = 2.9 to 3.4; and Low (L) = 2.8 and below.

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10.0 Appendix - Acronyms, Abbreviations and Symbols

AOU - add-on unit
ATU - advanced treatment unit
AUE - aerobic unit effluent
BOD_5 - 5-day biochemical oxygen demand
BT_{10} - breakthrough at Ce/Co = 0.10
cBODult - ultimate carbonaceous BOD
CF - continuity factor
cfu - colony forming unit
COC - constituent of concern
Ce - concentration in percolate
Co - concentration applied and/or at t=0
Cz - concentration at depth, z
CZG - clogging zone genesis
D.O. - dissolved oxygen
DSTE - domestic septic tank effluent
EPRI - Electric Power Research Institute
gpd - gallons per day
gpcd - gallons per capita per day
GIS - geographic information system
GW - ground water
H - high
HLR - hydraulic loading rate
HRT - hydraulic retention time
IRo - infiltration rate at time, 0
IRt - infiltration rate at time, t
IS - infiltrative surface
ISU - infiltrative surface utilization
ISUo - infiltrative surface utilization at t=0
ISZ - infiltrative surface zone
K - reaction rate constant
Ksat - saturated hydraulic conductivity
L - low
LF - loading factor
Lpcd - liters per capita per day
Lpd - liters per day
LPP - low pressure pipe
LTAR - long-term acceptance rate
M - moderate
MLR - mass loading rate
MPI - minutes per inch
nBOD - nitrogenous BOD
N - nitrogen
NSF - National Sanitation Foundation
O&M - operation and maintenance
P - phosphorus
pfu - plaque forming unit
PMB - porous media biofilter
RA - risk assessment
RM - risk management
SFE - sand filter effluent
SS, TSS - suspended solids
STE - septic tank effluent
t - time
tBOD - total BOD (cBODult + nBOD)
TMDL - total maximum daily loading
USEPA - U.S. Environ. Protection Agency
UV - ultraviolet light
VH - very high
VOCs - volatile organic compounds
VUE - volumetric utilization efficiency
WSAS - wastewater soil absorption system
z - depth below the infiltrative surface